CLIMED-FRUIT

ADAPTATION TO CLIMATE CHANGE AND MITIGATION FOR PERENNIAL CROPS IN MEDITERRANEAN AREA

Subtopics Review

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INTRODUCTION

The Mediterranean region is highly vulnerable to the impacts of climate change, with rising temperatures, erratic rainfall, and prolonged droughts threatening its agricultural productivity and ecosystem stability. Soil degradation, water scarcity, and extreme weather events pose significant challenges to perennial crops such as olives, grapes, and citrus, which are vital to the region's economy and cultural heritage. Addressing these challenges requires innovative and sustainable practices to enhance resilience, conserve biodiversity, and mitigate environmental impacts.

This document explores a comprehensive array of strategies tailored to the Mediterranean context, focusing on soil conservation, water management, biodiversity preservation, and adaptation of food chain processes. It highlights the importance of soil health through organic amendments, mulching, and reduced tillage, which improve carbon storage and fertility. Advanced irrigation techniques, such as deficit irrigation and smart systems, are presented as solutions to optimise water use in drought-prone areas. The role of biodiversity in fostering resilient agroecosystems is emphasised, with examples of genetic resource conservation, intercropping, and agroforestry. Additionally, the document examines post-harvest innovations, processing adaptations, and supply chain diversification to enhance economic and environmental sustainability.

This review, far from exhaustive, primarily draws on the results and practices tested within the CLIMED-FRUIT OGs, as well as other European projects and national/regional initiatives. It offers actionable insights for farmers, policymakers, and researchers. By adopting these practices, Mediterranean agriculture can adapt to climate change, reduce its ecological footprint, and ensure long-term productivity. The aim is to promote a transition towards sustainable and resilient farming systems that balance ecological health with economic viability, thereby safeguarding the region's agricultural heritage for future generations.

SUBTOPIC 1:
SOIL CONSERVATION AND CARBON STORAGE

Soils are a cornerstone of climate change adaptation and mitigation, especially in Mediterranean regions where land degradation, erosion, and fertility loss are increasingly exacerbated by rising temperatures and irregular rainfall. Beyond supporting plant growth, soils provide essential ecosystem services such as water retention, nutrient cycling and carbon sequestration. As recognised by European and international initiatives such as the '4 per 1000' and the EU Mission "A Soil Deal for Europe", restoring and maintaining healthy soils is fundamental to sustainable agricultural systems.

This chapter explores a range of soil management practices, including those selected within the CLIMED-FRUIT project, that contribute to erosion control, organic matter conservation and carbon storage in Mediterranean perennial cropping systems.

FERTILISATION PRACTICES TO IMPROVE SOIL QUALITY AND CARBON STORAGE

Organic amendments: spotlighting some good practices

The main objective of applying an organic amendment to agricultural soils is to improve organic matter content. Adding organic matter aims to achieve several objectives, including the maintaining or improving carbon stocks and soil properties and partially fulfilling the vines' nutrient requirements. The effect of applying organic amendments mainly depends on the environmental conditions that regulate microbial activity and on the agricultural practices and management, e.g., type of amendment, dosage, frequency and form of application, etc.

Practices based on the use of compost

As a slow-release amendment, compost can support ecosystem resilience by improving soil health, carbon dynamics and biomass productivity and increasing drought tolerance. Compost is obtained through an aerobic process of biomass degradation by microorganisms. Composting is implemented through three phases: 1. preparing the mixture of organic materials, 2. fermentation, 3. maturation and curing.

Agrocomposting: a way to improve soil quality and the local economy

The AGROCOMPOST project has conducted research and experiments on agrocomposting in the region of Valencia. It has facilitated training and carrying out collaborative experiences in situ with key stakeholders including farmers, cooperatives and rural administrations. These efforts have contributed to advancing the circular economy and attaining quality organic matter in rural areas in the region. Over five years, the project has been implemented at 195 pilot sites and led to the development of more than 420 composting processes from different raw materials, resulting in 15,400 tons of composted biomass. In terms of climate change mitigation, this represents more than 2,500 tons of carbon sequestered in the soils of vineyards and citrus and olive tree orchards.

On-farm compost

Recycling organic waste and residues through on-farm composting is a sustainable way to produce fertilisers for farm use. In this context, the OG OLTREBIO aimed to minimise farm inputs, recover farm waste and transfer composting process knowledge to other farmers. The first phase of the process involved preparing the piles after crushing and mixing the raw materials (Fig. 1.), i.e., crop residues mixed with grass cuttings. The pile was then covered with a sheet, and oxygenation was ensured by the aeration system, which was activated at regular intervals (ten minutes every two hours in the first two weeks). The temperature was measured continuously with two probes connected to a data logger, while the humidity was checked weekly (40–70%). To allow the homogenisation and fermentation of the materials, the pile was turned weekly twice in the first two weeks and once until the end of the process.

Fig. 1. On-farm composting at the CREA-AA experimental farm: 1. collection of farm waste; 2. shredding and mixing; 3. preparing and oxygenating the pile; 4. checking the temperature and humidity; 5. storing the mature compost; 6. application in the field [2]

Table 1 shows the main characteristics of the compost obtained. The parameters align with Italian legislation and highlight a good degree of maturity and quality of the compost. The mature compost was applied for three years as fertiliser in organic table grape vineyards (Sofia and Crimson Seedless varieties) in doses of 2.1 tons/ha. These applications allowed the farm to maintain the quality of table grapes and reduced the inputs and fuel used by the farm by 70% and 10%, respectively.

TABLE 1.
OG OLTREBIO COMPOST CHARACTERISATION: [2]

Parameters	Value
Dry matter (%)	76.2
pH	8.09
Total organic carbon (%)	20.85
Total nitrogen (%)	2.43
Carbon to nitrogen ratio (C:N)	8.58

On-farm compost tea

To improve organic production performance, the OG OLTREBIO tested the effect of compost tea (CT) in a cherry orchard (Lapins variety) and two vineyards (Sophia Seedless and Crimson Seedless varieties). The CT was obtained via the aqueous extraction of on-farm compost that was placed in a strainer bag with a tight mesh and immersed in a homemade bio-extractor and incubated for five days (Fig. 2.) [2]. The extraction was carried out with a ratio of 1:5 v/v (20%) and the oxygenation was obtained by activating a pump for 15 minutes every three hours [3]. Table 2 shows the main characteristics of the CT obtained. The pH values are around neutral, while the electrical conductivity (EC) was higher than 1.5 mS/cm, which suggested further dilution (1:15 v/v) [2].

TABLE 2.
OG OLTREBIO COMPOST TEA CHARACTERISATION: [2]

Parameters	pH	EC (mS/cm^2)	Nitrogen (mg/L)
Water	7.2	0.45	
Compost tea (1:5 v/v)	7.4	1.72	56.7

The CT was applied in an organic cherry orchard as soil treatment (3 L/tree) and foliar treatment (250 mL/tree) at the pink bud, post-fruit setting and veraison stages. In organic table grape vineyards, it was only applied to the soil in the dose of 1.5 L/vine at a shoot length of approximately 15 cm and in the post-fruit setting and veraison stages [3].

Fig. 2. Compost tea production at the CREA-AA experimental farm: 1. preparing the bag with the compost to be extracted; 2. aqueous extraction; 3. checking electrical conductivity and pH; 4. dilutions; 5. foliar application in the cherry orchard; 6. soil application in the vineyard [2]

The foliar application of CT favoured the crop's photosynthetic activity, acting as a biostimulant rather than a soil amendment. Moreover, the application of compost and compost tea significantly increased the fruit sugar content in table grapes, Sophia Seedless variety (17.40 °Brix) and cherries, Lapins variety (22.81 °Brix), compared to the control (15.67 and 20.63 °Brix, respectively) and contributed to improving the water condition of the plants compared to the control under severe water stress conditions (< -1.5 MPa). The same effect of foliar CT application in grapevines was observed in Egypt, with an improvement in fruit sugar content and anthocyanins [4].

Using green waste compost

A three-year experiment was conducted in France to evaluate the impact of green waste compost (one month composted) applied to sandy clay loam soil under the vine row. After annually applying around 126 t ha^{-1} of green waste over a three-year period, the organic matter content improved from 1.6% to 4.3% in the 0–20 cm horizon. Other parameters such as C:N ratio, microbial biomass and pH also improved. Moreover, green waste treatment significantly increased the number of earthworms collected, with the presence of several earthworm ecological categories, compared to the control (without amendment).

The OAD MO project also showed that the green waste compost significantly improved soil pH, from 6.3 in the control to 6.6 and 6.9 in the case of green waste compost and commercial compost, respectively.

Vermicompost: direct cooperation with earthworms

Vermicompost is the excreta of specific earthworm species that can improve soil health and nutrient status. Earthworm excreta (vermicast) are a nutritive organic fertiliser rich in humus, NPK, micronutrients and beneficial soil microbes, as well as nitrogen-fixing, phosphate-solubilising bacteria, actinomycetes and growth hormones such as auxins, gibberellins and cytokinins. Both vermicompost and its liquid extract (vermiwash) are growth promoters and crop plant protectors [5].

Vermicompost improves crop growth and yield, in addition to increasing the diversity and activity of antagonistic microbes and nematodes, which helps to suppress pests and diseases caused by soil-borne phytopathogens [6].

SOLUTION AVAILABLE ON THE MARKET[1]

Veraterra is the soil preparation biostimulant from VERAGROW. It is a complex vermicompost-based formulation, supplemented with seaweed extracts, that has multifaceted action:

- Stimulates microbial flora, with increased enzymatic activity in the degradation of organic matter and a significant increase in crop-stimulating symbiotic associations.
- Improves the physicochemical quality of the soil, with better nutrient storage capacity, reducing water loss and the risk of soil acidification or alkalinisation due to its buffering action.
- Improves nutrient bioavailability.

Fig. 3. Veraterra biostimulant (Veragrow) manufacturing process: 1) selection of active row ingredients, 2) production of rich and stable vermicompost, 3) extraction of the active principles and enrichment of the solution, 4) packaging in a practical size

1. *Veraterra is one of the winning technologies/products from the Crowd-Writing Contest organised by Climed-Fruit in 2023, aimed at private companies, to make mainstream farmers aware of the most recent innovations that promote resilience to climate change. See all winning technologies here.*

Mulching

Mulch is mainly used to control weeds or maintain soil moisture (for more details, see Subtopics 2 and 3). Made from different types of natural materials, it also has the side effect of improving soil health once it has deteriorated.

The effect of no-till rice straw mulching on soil health parameters, including soil organic carbon (SOC), was evaluated in two citrus plantations on the Valencian coastal plain in Spain; these plantations are jointly representative of the semi-arid hot-summer Mediterranean climate on flat lands [7]. The straw mulch reduced soil temperature and favoured root growth fourfold as well as soil macrofauna development. Under the straw mulch, the macroporosity was between two and 14 times higher, and the SOC mass fraction increased 10% more than in the bare soil. However, the beneficial effects of straw mulching on soil health are limited after three years of treatment. It is recommended to add organic fertilisers and/or amendments alongside a surface tillage operation [7].

Using straw mulch around newly planted perennial crops has been shown to improve plant growth, reduce mortality and enhance recovery speed [8]. Non-irrigated grafted apple trees were planted during a trial in France in 2023 and two modalities were implemented: one mulched and the other hoed and fertilised with 60 units of nitrogen per year. At the time of regrowth, the plot that had been mulched had a mortality rate of 12%, while the plot that had been tilled and fertilised had a mortality rate of 20%. The growth of the graft was measured at the end of August. The control group shoot length was 18 cm on average, while for the mulched group, which was not fertilised, it was 27.5 cm on average. This increase in growth is often observed, particularly in well-drained or poor soil conditions [8]).

The VITIMULCH project tested different types of mulch under vine rows in the south of France for three years between 2020 and 2023. Different materials were used under the rows: crushed oyster shells, wood bark, wood chips, composted green waste, vine shoots, plant-based felts, etc., as shown in Fig. 4. Each type of mulch was installed to a height of around 15–20 cm and a width of 60 cm.

Fig. 4. Different types of mulches under the row at the time of installation as part of the VITIMULCH project, Gaillac, France

The different mulches improved the physical and chemical soil attributes and enhanced soil moisture levels (see Subtopic 3). For example, the three-year application of wood chips under the row has improved soil organic matter from 1.8% to 2.5% and positively affected earthworm count compared to chemically weeded rows. The initial results illustrated in Fig. 5. show the impact of different types of mulches on soil earthworms after their deterioration.

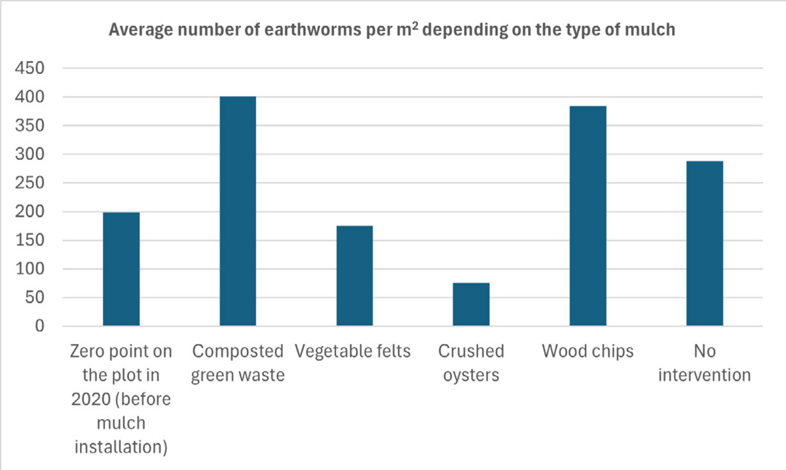

Fig. 5. Abundance of earthworms (average number per m²) depending on the type of mulch. From left to right: zero point on the plot in 2020 (before mulch installation), composted green waste, vegetable felts, crushed oysters, wood chips, no intervention – VITIMULCH project

Crop residues and by-products

Using pruning residues

Citrus growers used to burn pruning debris but this practice is now restricted, as it causes environmental risks and possible risks to human health, as well as contributes to CO_2 emissions into the atmosphere. It is recommended to lay citrus pruning debris to cover at least 30% (50% for fruit trees such as olives or almonds) of the soil surface between rows. Placing this debris on the surface of the soil creates a protective layer that reduces erosion and keeps the soil humid as it reduces water evaporation. In addition, there is an increase in soil organic matter and the soil carbon generated. It also provides a refuge for fauna. The 'Improvement of the soil and the plant from enriched pruning remains' project has correctly shown that the application of shredded citrus pruning remains, enriched with grass and legumes grown as cover crops, doubled soil biological activity compared to the control, favoured soil water storage and increased soil organic carbon storage. This experiment illustrates the positive impact of reusing pruning debris in the field rather than removing or burning it.

Moreover, the OG Carbocert evaluated the benefits of integrating pruning debris in vineyards and citrus, olive and almond orchards by spreading this debris on the ground surface in the inter-row. To do this correctly, the debris must be chopped or shredded before spreading (Fig. 6.).

The chopped or shredded debris must be small enough to prevent the formation of clods where pests may nest, to avoid hindering other operations in the orchard/vineyard (treatments, sowing, etc.) and to facilitate the decomposition of the debris. Slow decomposition means carbon is introduced gradually and over a long period, and this can increase the organic carbon content in soil surface layers by 60%. When these practices are combined with mulching, this increase reaches 73% (results for viticulture). In fruit orchards, the OG Carbocert evaluated a carbon sequestration potential close to 1.5 t ha^{-1} $year^{-1}$.

Fig. 6. Managing pruning debris cover in a citrus crop (photo: LIFE Low Carbon Feed) and shredding before application in the alley

Recycling crop by-products

Almond hull and shell reuse

Recycling almond hulls and shells (Fig. 7) as organic amendments in orchards enhances soil microbial biomass and activity, promoting soil health, nutrient cycling and carbon storage. Results of a field trial conducted in California on irrigated loam soil showed that surface-applied hull/shell amendments significantly increased microbial biomass with bacteria and fungi compared to controls [9] This organic layer supported diverse microbial communities and improved soil multifunctionality and microbial activity. The amendments decomposed by 45% within a year, lowering the C:N ratio of the amendment from 53:1 to 29:1, with no negative impact on tree nitrogen status or yields. Additionally, almond root biomass density doubled in amended soils, highlighting the organic layer's role in fostering root growth and improving soil conditions.

Fig. 7. Photos of hull and shell one ton per acre (top) and shell one ton per acre (bottom) treatments in a location in Merced County in 2017 during March (left), April (middle) and July (right). Source: [10]

Effluent recovery: an example in viticulture

The WETWINE project developed wine waste recovery technology that offers a sludge treatment alternative with low installation and minimal energy requirements. The winery's wastewater passes through an anaerobic hydrolytic digester, where the initial purification takes place. The liquid part is then sent to subsurface flow constructed wetlands (SSSCW) where the water is treated using a combination of vertical and horizontal SSCW planted with reeds. The solid part is sent to a sludge treatment wetland for anaerobic stabilisation, and the sludge can be recycled as an organic soil amendment for the vineyards as part of the circular economy. The composition of the sludge produced is highly variable, depending on the local agroclimatic conditions and the origin of the sludge.

The technology demonstrated that winegrowing sludge is harmless and can be incorporated into vineyards in an easy, economical and ecological manner. However, it has a less pronounced impact on soil quality than commercial soil improvers, which contain more nutrients. Further study and a full-scale installation are necessary before larger-scale trials can be conducted.

Biochar

Biochar, a carbon-based substance made from organic waste pyrolysis, is promising for increasing carbon content in Mediterranean areas. Biochar has been added to the EU Fertilizer Regulation [11] and is authorised in organic agricultural production [12]. In Spain, biochar application of 100 t ha^{-1} (20 t ha^{-1} $year^{-1}$), increased total organic carbon (TOC) of 10–30 g Kg^{-1}, and in another experiment TOC doubled after two years of biochar application of 60 t ha^{-1}.In Italy, after two years of biochar application, there was an increase in available soil water content (3.2%/45% for the 16.5/33 t ha^{-1} application rates, respectively) and leaf water potential (24–37%) during droughts. Moreover, grape yield per plant significantly increased for four years after the first biochar application, ranging from 16% to 60%. The effect of biochar on yield was found to be higher in the years with the lowest rainfall, suggesting a protective effect of biochar against plant water stress [13]

Comparison of different amendments in soil carbon storage

The OAD MO project has conducted eight years of experiments on the application of organic matter in viticultural soils, including green waste compost, commercial compost, pomace compost and cover crops. The results show that organic amendments improve soil carbon content and organic matter content, although significant differences between the different types of organic matter tested are rare, due to the slow evolution of soil carbon levels and the heterogeneity of carbon distribution. Organic amendments also provide mineral elements such as nitrogen, phosphorus, potassium, calcium and magnesium, which are available to vines in the medium to long term.

The data was used to parameterise and validate the AMG model for viticulture, which calculates changes in organic carbon stock over the long term. A prototype simulation tool was developed to provide a decision support tool for farmers. Simulations of the evolution of the carbon stock for different cultivation practice scenarios, starting from an initial situation, were carried out on different vineyards and for different soil situations. Three scenarios were analysed for the study case of a Languedoc vineyard with the stony alluvial soil typical of Costières de Nîmes:

- Reference scenario: mechanical weeding of all inter-rows and input of green waste compost (25 tons every four years, 36% MO, ISMO 60)
- Scenario 1: temporary cover crop in all inter-rows, application of 25 tons of green waste compost every four years (36% MO, ISMO 65) and pruning debris left on the soil
- Scenario 2: mechanical weeding and pruning debris
- Scenario 3: pruning residues and temporary cover crops in every alley

This simulation showed that the soil carbon provided by the organic amendment (green waste compost) is much higher than that provided by the grass cover (around five times higher) (Fig. 8). The AMG model predicted an increase in soil carbon stock of 2 t ha^{-1} after around 15 years of temporary grass cover application. In addition, the application of organic amendment could significantly increase soil carbon stock by 10 and 15 t C/ha by 2050.

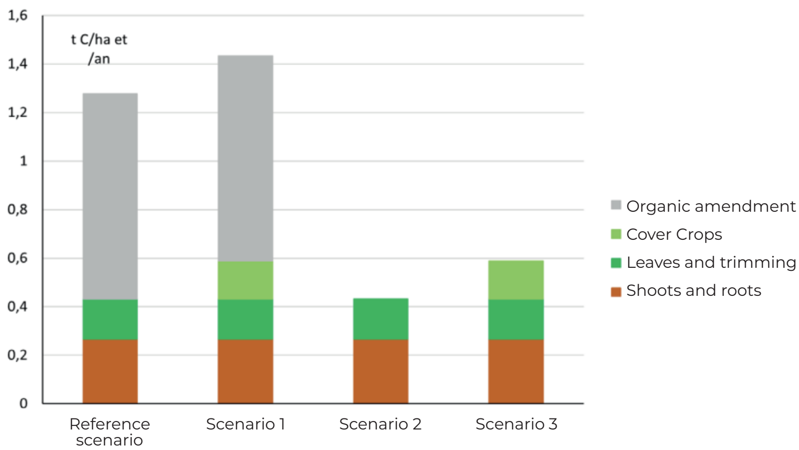

Fig. 8. Results of simulation using the OAD MO in the Languedoc vineyard study case [14]

SOIL COVER CROPS AND REDUCED TILLAGE IN PERENNIAL CROPS TO ENHANCE SOIL QUALITY

To increase soil organic carbon (SOC) sequestration in the Mediterranean, cover crop selection and management in perennial crops must consider factors such as soil fertility, plant community composition, termination method, debris management and soil disturbance regime. Moreover, the potential of cover cropping depends on climate, management and microbial community changes.

Grass cover

Managing spontaneous permanent cover in almond orchards

The objective of permanent grass cover is to maintain and nurture plant cover between the rows, whether spontaneous or sown. The OG CARBOCERT examined the implementation of this practice in almond orchards (Spain), to assess its impact on soil and provide technical advice. The most effective practice to sequester carbon in the soil is a spontaneous cover crop, with the recommendation to use mainly cutting tools (mowers, strimmers, brush cutters) or very superficial tillage to maintain it and to always leave the plant residues on the surface. These same management types are recommended for weed control in the row and could be combined, for greater efficiency, with mulching, obtained either from mowing the cover itself (Fig. 9) or from external inputs (prioritising natural and local mulching). Sheep or goats can also be used for cover control in all perennial crops (including olive groves as shown in Fig. 9), with the advantage of also providing additional organic matter to the soil. Grazing is advisable only during winter dormancy since the animals also graze the lower branches.

Fig. 9. Spontaneous vegetation cover maintained by mowing in almond orchards (left) and sheep used for cover control in an olive grove - OG CARBOCERT

To limit water and nutrient competition, the most efficient covers are those with an opposite vegetative cycle to the almond tree cycle. Such cover should be in place between the almond senescence phase and up to floral initiation and should wither naturally from floral differentiation to post-harvest if possible. To help ensure the most favourable composition of the spontaneous cover, mowing can be planned to encourage the natural reseeding of the desired species and prevent undesired species from flowering.

Grass cover in the rows

The implementation of natural grass cover is a straightforward process, whereas the use of sown grass cover, or turf cover, can control water and nutrient competition more effectively through the selection of appropriate species, varieties or mixtures. An experiment conducted on vines by IFV has demonstrated that in the first few years, *Koeleria*-based mixtures had the lowest impact on vine vigour. As for natural grass cover, its impact on the vines has tended to increase over the years, in parallel with its rate of coverage in the rows. The introduction of legumes is one of the solutions currently being tested to manage nitrogen competition.

The OG IOCONCIV studied the use of a self-reseeding cover crop in the rows in Tuscany, Italy. The permanent cover sown in the rows was *Trifolium subterraneum* ssp. *brachycalicinum* for its self-seeding capacity, allowing different cycles for 3–4 years. The *brachycalicinum* subspecies has evolved to tolerate dry soils and is better suited to sub-alkaline, silty clay loam soils. The clover biomass serves as a living mulch in autumn, winter and spring, transitioning to a dead mulch in summer, with the effect of minimising competition with grapevines for water and nutrients and reducing drought stress due to the soil coverage during the summer. At the end of summer, the spontaneous germination of clover seeds initiates a new biological cycle in the rows, offering benefits such as suppressing weed emergence and improving soil fertility.

Green manure and intercropping

Green manure is a plant cover crop that produces biomass and is returned to the soil to improve its fertility and structure if water and nutrient competition are kept under control. This is challenging but can be of real interest in the context of the poor Mediterranean soils. The date, type of destruction and choice of species are important factors for the proper implementation of this practice. Green manure can influence the supply of nitrogen to the crop, thus limiting the use of inputs [15].

Intercropping involves growing two or more crops in proximity to each other. The end goal of intercropping is to increase the yield per hectare and unit, and this is possible through better use of the resources in the soil that would otherwise be used by a single crop. Both crops can be harvested or not.

Example of green manure implementation in a Mediterranean vineyard

During an experiment carried out in a vineyard in France, it was measured that approximately 62% of the carbon in terminated green manure biomass was mineralised, while the remainder was classified as 'stable' carbon, as indicated by the organic matter stability index (OMSI) [16]. The OMSI is a measure of the product's potential to store carbon in the soil, expressed as a percentage of the product's organic matter. The closer the OMSI value is to 100%,indicates that the carbon provided by the green manure will remain in the soil for an extended period. Calculations have been conducted to determine the theoretical carbon storage capacity of green manures. For instance, green manure of 4 tons dry matter ha^{-1} (sown in all the inter-rows), represents 1,600 kg C ha^{-1}, i.e., 608 kg of stable carbon per ha (OMSI 38%). In the case of green manure sown in alternate rows, the potential carbon storage is 200 kg/ha, i.e., 50 kg C/t DM. This carbon storage varies little depending on the green manure species used as they all have the same organic matter stability index [16].

In the Mediterranean context, sowing green manure as early as possible (late August/early September) will ensure that the seedlings are well-developed during heavy rainfall in autumn, to reduce erosion and prevent vine leaves from getting blown away (they are a source of nutrients for the soil). Overdosing seedlings (for all species) is also advisable in Mediterranean conditions, as well as choosing a well-diversified mix (legumes, grasses, brassicas) to ensure the sustainability of the cover with rotation of the dominant species.

The choice of termination method depends on the objectives being pursued. Grinding or mowing in spring destroys the aerial parts and allows them to dry out. Mowing or rolling can be useful to mulch and maintain the soil without chemical weeding or tillage. In a Mediterranean context, it is advisable to terminate the cover crop in early spring to avoid too much water competition, which would also have an impact on the mineralisation of the cover crop once it was terminated.

Meeting the 4‰ initiative goals in olive groves through intercropping

The DIVERFARMING project implemented a three-year study in a traditional rainfed olive orchard in southern Spain, with alley cropping with minimum tillage compared to conventional tillage, focusing on soil organic carbon and soil quality. Three intercropping strategies — *Crocus sativus* (D-S), *Vicia sativa* and *Avena sativa* in rotation (D-O), and Lavandula x intermedia (D-L) — were tested compared to the control with conventional tillage. Intercropping increased soil organic content in the topsoil (0–10 cm) by 41.1% (D-S), 28.5% (D-O) and 30.5% (D-L). No significant differences were observed in soil quality indices, but intercropping met the 4‰ initiative goals, with an annual increase in soil carbon per hectare and year of 80% (D-S), 87.4% (D-O) and 86.4% (D-L). This highlights the potential of intercropping to enhance carbon storage and improve soil sustainability in the short term [17].

Comparing cover crops and their effects on soil in cherry and almond orchards

The effects of different cover crops, mechanical cultivation and herbicide treatments on soil organic matter content and soil physical properties were investigated in a cherry orchard with clay soil located in the Northern region of Turkey, for two years [18].

Trifolium repens L. (TR), *Festuca rubra subsp.* Rubra (FRR), *Festuca arundinacea* (FA), *T. repens* (40%)+*F. rubra rubra* (30%)+*F. arundinacea* (30%) mixture (TFF), *Vicia villosa* (VV) and *Trifolium meneghinianum* (TM) were used as cover crops. The cover crops were mowed in the flowering period. After 90 days following seed harvest, soil samples were collected from two depths (0–20 cm and 20–40 cm) in each plot. TR and VV treatments increased soil organic matter content at 0–20 cm soil depth compared to untreated control plots (Fig. 10) [18].

A field experiment was also conducted in Cordoba, Spain on drip-irrigated 10-year-old Guara variety almond trees during two seasons, to examine the soil nitrogen and carbon sequestration potential of three seeded cover crops (barley, hairy vetch and a mixture of 65% barley and 35% vetch) and control of spontaneous flora. Regarding the soil fertility in terms of soil nitrate, the best results were observed for the vetch (Fig. 11), with soil nitrate content improved by over 35%, while the mixture and barley cover crops had a higher potential for carbon sequestration, increasing the soil organic carbon by more than 1.0 Mg ha^{-1} during the study period (Fig. 12) [19].

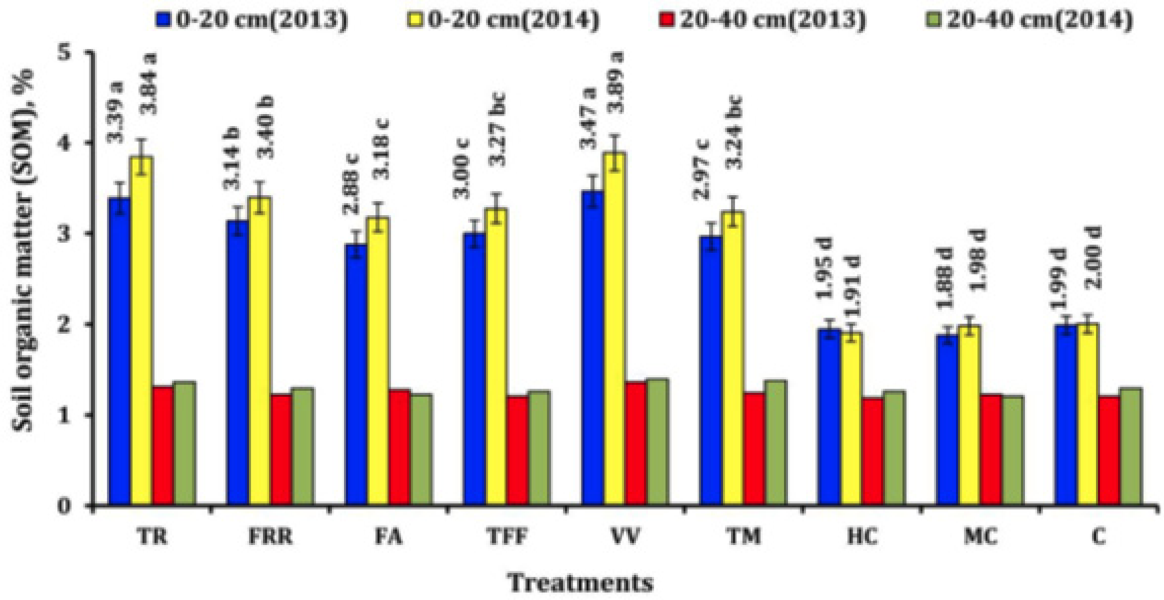

Fig. 10. Effects of cover crops and other treatments on soil organic matter (SOM) at 0–20 cm and 20–40 cm soil depths in a cherry orchard with clay soil. Trifolium repens L. (TR), Festuca rubra rubra L. (FRR), Festuca arundinacea (FA), T. repens (40%)+F. rubra rubra (30%)+F. Arundinacea (30%) mixture (TFF), Vicia villosa (VV), Trifolium meneghinianum (TM), a mechanically cultivated plot (MC), herbicide treatment (HC) and control plot (C) [18]

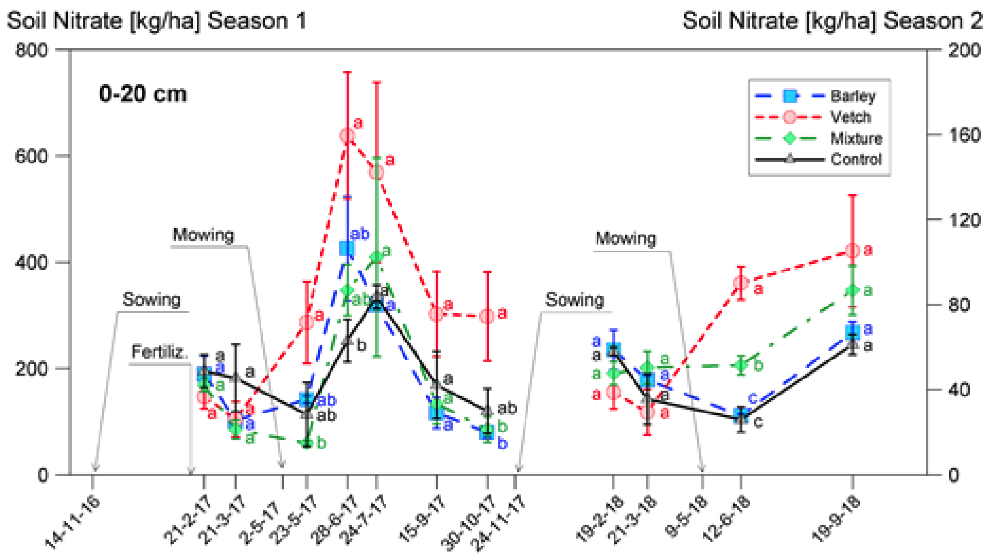

Fig. 11. Soil nitrate content at 0–20 cm soil depth during the two monitoring seasons.

Barley (blue square), vetch (red circle), mixture (green rhombus), control (black triangle) [19]

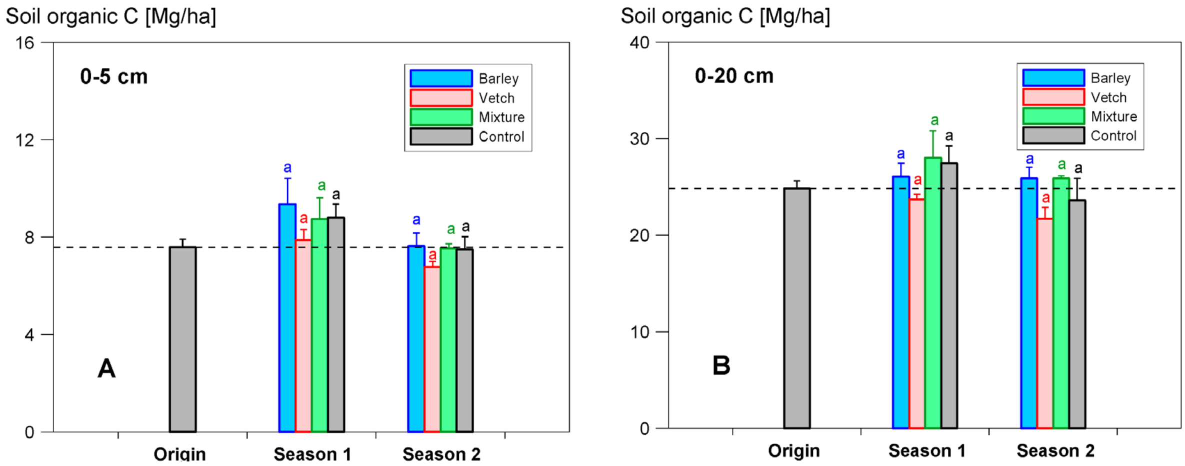

Fig. 12. Soil organic carbon at the beginning and end of the experiment during the study period at 0–5 cm (A) and 0–20 cm soil depth (B) [19]

Conservation tillage

Conservation tillage refers to a set of soil management practices aimed at reducing soil disturbance, maintaining organic matter and minimising erosion while enhancing water infiltration and retention. Conservation tillage goes hand in hand with the soil cover practices mentioned above. It can be summarised in three key principles:

- Minimal soil disturbance: limits the frequency and depth of tillage to avoid disrupting soil structure and microbial activity.
- Soil cover: keeps the soil covered with crop residues, cover crops or natural vegetation to prevent erosion and retain moisture.
- Crop rotations or cover crops: enhances biodiversity, improves nutrient cycling and reduces pest and disease pressures.

Tillage affects soil bacterial communities by reducing soil organic matter as a source of carbon and nutrients, changing soil moisture and temperature and decreasing the proportion of stable macroaggregates, which provide a friendly microhabitat for bacteria [20]. Previous studies have shown that reduced tillage significantly increases the soil organic content at the 0–10/30 cm depth compared with conventional tillage, regardless of the climate conditions, soil type and cropping system [21].

The more intensive the ploughing, the poorer the soil. The GASCOGN'INNOV project demonstrated that reducing the intensity of tillage and increasing the duration of plant cover can enhance the abundance of all organisms under study (earthworms, nematodes, bacteria and fungi), although not necessarily their diversity.

AGROFORESTRY AND HEDGES FOR CARBON STORAGE AND SOIL CONSERVATION

Trees and hedges play a crucial role in shaping soil fertility and carbon storage since they act as carbon sinks by absorbing atmospheric CO_2 through photosynthesis and storing it in their biomass (wood, roots, leaves) and the soil through root systems and organic matter.

Agroforestry

Perennial crops and management practices such as no-tillage, residue mulching, extended crop rotation and cover cropping are strategies that may contribute to the soil carbon stock in Mediterranean areas, contributing to reducing agricultural GHG emissions. By combining some of these characteristics, agroforestry systems have great mitigation potential through carbon sequestration. Of the agroforestry systems in the Iberian Peninsula, in southern Europe, the *montado* in Portugal and *dehesa* in Spain are of great significance. They consist mostly of multipurpose trees such as chestnuts (*Castanea* spp.), oaks (*Quercus* spp.) and olives (*Olea europa* L.) with understory vegetation such as pastures extensively grazed by livestock (sheep, black pigs and cattle), usually in a rotation scheme [22].

Mediterranean agroforestry systems generally have low soil fertility and are limited by their shallow soil depth and low water and nutrient availability, resulting in natural pastures with poor productivity and quality. After noticing the low productivity of pastures, farmers in the Iberian Peninsula began to sow legume-rich mixture pastures (Fig. 13), which contributed to a simultaneous increase in pasture productivity and soil organic carbon concentration as well as prevented soil degradation [22].

Fig. 13. Partial view of a Portuguese agroforestry system with Quercus sp. and a biodiverse pasture [22]

Together with the trees, permanent pastures (natural or improved) also provide a fast way to build soil carbon, generating a significantly higher amount of organic carbon in the 0–10 cm soil layer beneath the tree canopy in both unmanaged (2.4 kg C m^{-2}) and improved (3.1 kg C m^{-2}) Spanish pastures, as compared with the open field (1.8 and 2.1 kg C m^{-2} in natural and improved pastures, respectively) [23].

Hedgerows

Hedgerows are often where different ecosystems meet, such as the boundary between forests and agricultural land. These areas are often characterised by enhanced biodiversity and a higher rate of nutrient exchange. In the Mediterranean, hedgerows between woodlands, scrublands and agricultural fields can act as dynamic zones for nutrient cycling, water retention, organic matter accumulation and wind control. Therefore, they have similar effects on soil conservation as those mentioned above for agroforestry. Hedgerows can also reduce runoff and thus organic matter loss through soil erosion. Based on a literature review [24], hedgerows contribute to additional carbon storage of 750 kg C/ha^{-1} per hedge $year^{-1}$. However, it is generally difficult to establish a hedgerow due to a lack of space once the vineyard or orchard is in place. In such cases, it is advisable to implement smaller shrub hedges along the boundaries of the plot.

Simulating carbon storage with hedges in winegrowing

Carbon storage associated with planting hedges around vine plots can be estimated using a carbon footprint calculator.

For example, on a farm scale, each vineyard plot can be framed with mixed hedgerows and broken up by adding intra-parcel shrub hedges. Mixed hedgerows are larger than shrub hedges. They contain tall trees and high and low shrubs that form a high stratum and an intermediate stratum. The particular soil type and climatic conditions will determine the choice of species. This simulation example considered a large 30-hectare plot, with 2600 linear metres of mixed hedgerow planted, corresponding to 90 linear metres per hectare. In addition, shrubby hedges are planted every 60 metres between the rows of vines, corresponding to 150 linear metres of intra-parcel hedges per hectare. Thus, we have high, voluminous hedgerows around the plot and smaller hedges interspersed with the vine rows within the plot.

- Carbon storage of a mixed hedgerow positioned around the plot, at a rate of 90 linear metres per hectare: 280 kg eqCO_2/ha/year (calculated using the GES&VIT tool developed by IFV).
- Carbon storage in shrub hedges alternating with rows of vines, to break up the plot, at a rate of 150 linear metres per hectare: 330 kg eqCO_2/ha/year.

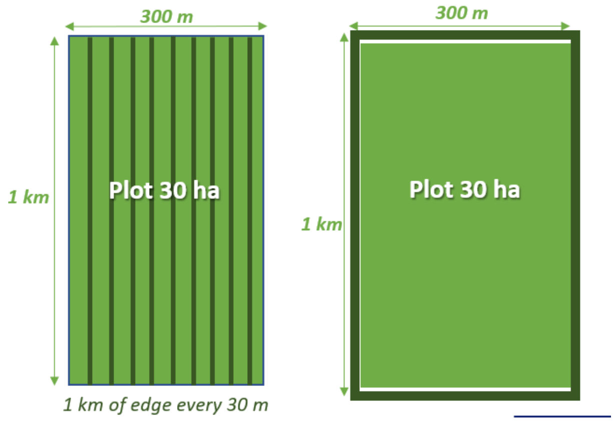

Fig.14: Left – Intra-parcel hedges: for 30 ha, there is a hedge every 30 m, i.e., 150 linear metres/ha of intra-parcel hedges
Right – Hedgerows around the plot: for 30 ha, there are 2600 linear metres of perimeter, i.e., 90 linear metres/ha of hedgerow around the perimeter

These storage values are calculated based on figures from the Bas Carbone label (low-carbon standard) hedgerow method and ADEME's Carbocage project [25].

Good to know:

- **Favour north-south orientations to limit and balance the shade from trees and shrubs on the vines.**
- **Leave a minimum distance of 3 to 4 metres between the hedge and vine row.**

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SUBTOPIC 2:
IMPROVING RESILIENCE TO CLIMATIC HAZARDS

Mediterranean perennial cropping systems are increasingly exposed to climatic hazards such as heatwaves, late frosts, windstorms and hail, all of which jeopardise yield stability, fruit quality and long-term sustainability. In addition to reducing emissions, adaptation strategies must also enhance the resilience of agroecosystems to these acute and chronic stresses.

This chapter presents a selection of practical approaches and innovative techniques that strengthen the capacity of Mediterranean orchards and vineyards to withstand and recover from climatic extremes, focusing on structural, biological and technical levers.

RESISTANCE TO EXTREME DROUGHT AND HEAT WAVES

The analysis of temperature trends over the last 120 years underscores that the Mediterranean Basin has been warming more rapidly, about 20% faster than the global average [1]. This trend is causing real and severe damage to Mediterranean perennial crops, leading to a decrease in fruit tree productivity and quality. The situation demands immediate action to develop adaptive strategies combining sustainable farming practices and investment in climate-resilient infrastructures (i.e., shading nets and drought-tolerant plant material).

Shading nets

Shading nets protect perennial crops from extreme drought and heatwaves. Although the costs of their installation can be significant, they also protect against hail and reduce vulnerability to climatic hazards in general.

In viticulture, the VITISAD project showed that shading nets reduce exposure to sunburn by attenuating the radiation and delaying the ripening process by five days, thus optimizing wine quality. Berry ripeness parameters were also impacted, with lower sugar and higher acidity, increased assimilable nitrogen content of musts by ~20% and decreased colour and phenolic compounds in red wines. Moreover, vines with nets were less stressed under water deficit. The RESILVINE project investigated the impact of different shading net colours on the ripening dynamics and production of sparkling wine grapes (var. Chardonnay) (Fig 1.). The shading nets reduced the incidence of global solar radiation and significantly decreased berry temperature under direct solar light, with an increase in sugar accumulation under white nets. The shading nets' performance was confirmed in terms of the effect on the vineyard microclimate.

Name	Plot	Shading %
CON	Control	0
WHT	White	30
LGR	Light Green	8
DGR	Dark Green	19
BLK	Black	26

Fig. 1. RESILVINE project, Ferghettina farm

Blue and white shading nets (20% shading intensity, Fig. 2) appear to reduce average canopy temperature in Hass avocado trees [2,3,4].

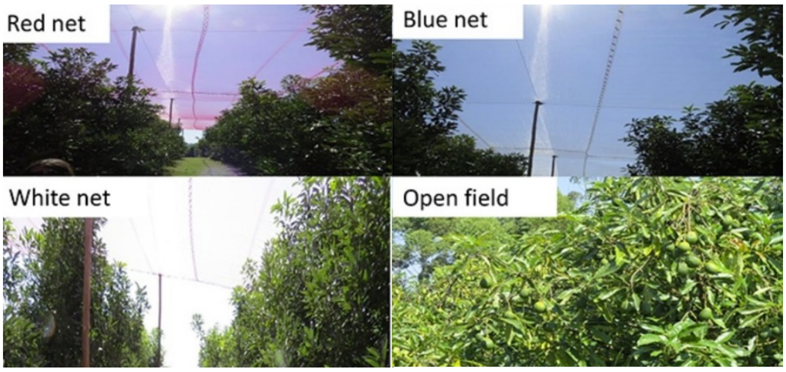

Fig. 2. Shading nets in an avocado orchard [2]

Shading nets are also a valuable tool in sweet cherry production, offering several benefits such as sun protection, temperature regulation, uniform fruit ripening, improved yield and water conservation. The appropriate shading percentage should be decided based on local climate conditions and the needs of the cherry variety (typically 30–40% shade) [5].

Foliar applications

In olive tree management, using foliar applications of kaolin, salicylic acid and abscisic acid, either combined or alone, can be an effective strategy to mitigate the impacts of drought and heat waves. Kaolin, a natural clay mineral, acts as a physical barrier on the leaves, reducing water loss through transpiration and providing some protection against heat stress. Salicylic acid is known for its role in plant defence mechanisms and can help olive trees to better withstand environmental stresses. Abscisic acid is a plant hormone that regulates responses to drought and can help olive trees conserve water and adjust their growth patterns during water scarcity. The Portuguese Operational Group New Practices in Rainfed Olive Groves explored the effects of different natural substances that induce resistance mechanisms with a protective effect against adverse environmental factors. Applying salicylic acid and kaolin significantly increased olive productivity (Fig. 3), and the olive oil quality was not negatively affected [6]. Moreover, applying abscisic acid demonstrated a medium- to long-term effect (Fig. 4) on the trees' water status, contributing to increasing the trees' resilience to summer stress drought and delaying the adverse effects of drought. The trees' physiological and biochemical functions were also improved during recovery since their capacity to recover from previous drought depends on the severity of the damage caused by the prior stress [7]. However, it is important to follow recommended application rates and timings to ensure the effectiveness of the strategy.

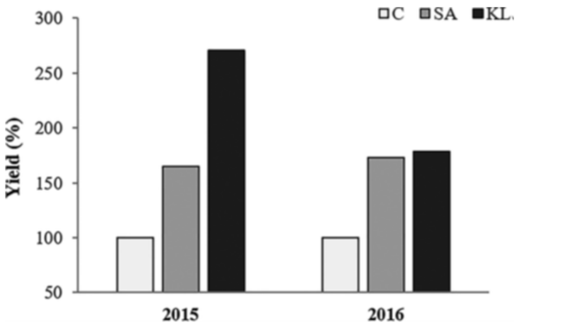

Fig. 3. Influence of salicylic acid (SA) and kaolin (KL) treatments on olive yield in two years of experiment [6]

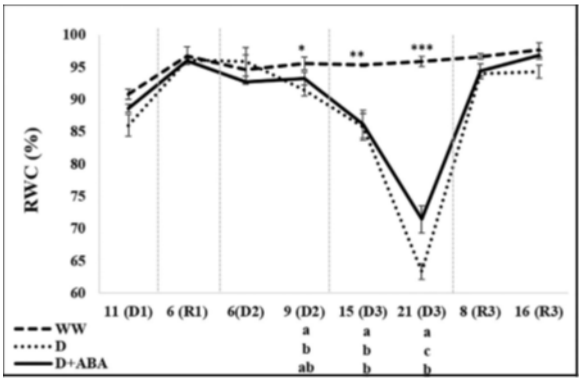

Fig. 4. Changes in relative water content (RWC) over days of drought (D1, D2, D3) and recovery (R1, R3) in each cycle, in leaves of well-watered (WW) and drought without (D) and with abscisic acid (D + ABA) plants [7]

Applying kaolin on vine leaves can also be a good strategy to face heat waves due to kaolin's capacity to reflect ultraviolet light, which can reduce leaf and fruit temperature by up to 5°C. Cooperation Projects Generalitat Valenciana observed that kaolin applications in a Marselan vineyard in Spain (Fig. 5) enable better wine quality with colour intensity and a higher concentration of tannins and aromatic components.

Fig. 5. Use of kaolin in a Marselan vineyard (Bodegas Enguera)

Dry farming practices

Dry farming involves a combination of farming techniques that require minimal water input. These practices are beneficial in areas prone to drought and heat waves, as they can help reduce water usage and increase soil health and resilience. Some common dry farming techniques include mulching, cover cropping and planting drought-resistant crop varieties.

Using mulching techniques and cover crops

The DRIVE LIFE project investigated innovative solutions for vineyard management to reduce drought effects by developing soil and canopy management techniques to improve water resilience. Different winter cover crop mixtures were sown between the rows after harvest in vineyards located in northwestern Italy. Cover crops were terminated in late spring using different techniques (Fig. 6), which increased soil water storage by up to 10%. Sub-row mulching enabled water savings with positive leaf water potential during the season. Some ecosystem services (soil carbon sequestration, pollination and counteraction to soil erosion) were also improved. The seed mixture composition affected the grape composition: cereal-based grassing led to higher sugar content, while legume-based mixtures led to higher acidity and available nitrogen. However, the effectiveness of the proposed techniques is strongly linked to seasonal weather trends, which have an impact on biomass production and additional water use.

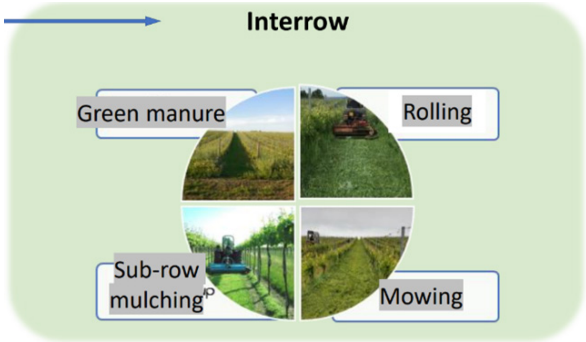

Fig. 6. Cover crops terminated in late spring

Different types of exogenous mulches (for example, wood chips, green waste compost, woven cellulose or lignin, straw, bio-sourced plastic, etc.) can be used in dry farming with several advantages: reducing the need for herbicides when placed under the crop row, maintaining soil moisture (up to 20% in a very dry vintage compared to bare soil), reducing erosion and providing organic matter. The efficiency and durability of the mulches vary depending on the material used, but covered soil is more resilient than bare soil (cooler, wetter, more microbial activity).

The Operational Group GO CITRICS applied rice straw from Albufera Natural Park in Valencia (Spain) as mulch in citrus groves. One of the main benefits observed is this material's capacity to retain moisture in the soil, which is particularly relevant for citrus fruits since they increase in size in the months of greatest water need. Rice straw helps to control weeds and maintain a more stable soil temperature, protecting citrus roots from thermal stress and maintaining biological processes that occur in the first few centimetres of soil, such as the mobilisation of nutritional elements by microorganism consortia. Another key aspect is that the decomposition of rice straw enriches the soil with organic matter, improving its structure and fertility. Finally, the use of rice straw as mulching material contributes to carbon capture, helping to reduce greenhouse gas emissions. As an agricultural by-product, its reuse avoids open burning, a practice that generates polluting emissions.

Adapting plant material

Plants develop several mechanisms to cope with water scarcity and high temperatures, such as deep root systems, efficient water use and heat tolerance. The impact of extreme weather events on ecosystems and agriculture can be mitigated by using better-adapted varieties without incurring additional costs. The following section gives some examples of varieties of interest, due to their tolerance to heat and drought, in viticulture, oliviculture and nuts.

In viticulture, among the widely used drought-tolerant rootstocks, 110 Richter, 140 Ru, 44-53M and SO4 present several common features: deep or branched rooting, high water extraction capacity, good hydraulic transfer, influence on canopy development or control of transpiratory losses. In France, the PHYSIOPATH project has measured the resistance to xylem vessel embolism – another parameter to assess drought tolerance – of 23 varieties and three rootstocks. The results enabled varieties and rootstocks to be classified according to their drought tolerance.

In oliviculture, the ancient varieties used in traditional orchards are generally relatively tolerant to drought. New varieties or clones, specifically those designed for the intensive planting systems of super high-density modern olive groves, still need to be assessed for their drought tolerance, however. The O4C project compared some olive varieties from the arid or desert areas of the eastern and southern Mediterranean basin with the best international varieties in terms of plant growth and fruit production. The Syrian cultivars Barri, Maarri and Abou Satl Mohazama, among others, performed similarly to the best international cultivars, such as Arbequina, in tree architecture, early bearing and fruit production. In addition, leaf macro-characteristics were used to evaluate the drought tolerance of 32 olive cultivars [8], where Lechin de Sevilla and Picholine Marocaine turned out to be the most drought-tolerant.

SOLUTION AVAILABLE ON THE MARKET: OPTIMISING SOIL STRUCTURE THROUGH THE ADDITION OF COMPOST[1]

An example of one such product that can be used, identified through CLIMED-FRUIT's Open Contest, collecting existing solutions on the market from providers, is Veraleaf®, a complex vermicompost-based formulation complemented by seaweed and plant extracts with an impact on (i) nutrient assimilation through humic and fulvic substances and symbiotic associations; (ii) growth due to vermicompost phytohormones and complex sugars, which stimulate cell division and elongation; (iii) anti-stress effect, provided by polysaccharides, amino acids and phenolic compounds that reduce the impact of abiotic stresses (hydric, thermal, etc.) and enable the plant to maintain its potential yield.

1. Veraleaf is one of the winning technologies/products from the Crowd-Writing Contest organised by Climed-Fruit in 2023, aimed at private companies, to make mainstream farmers aware of the most recent innovations that promote resilience to climate change. See all winning technologies here.

Drought is also one of the main factors affecting sweet cherry yields. Cherry rootstocks can provide a range of tree vigour levels that correspond to the characteristics of the soil. Besides *Prunus mahaleb* seedlings, a new generation of rootstock adapted to dry and hot climates is now available, such as WeiGi®. A six-year experiment in France demonstrated that WeiGi® in the Regina variety showed good growth, with a yield 50% higher than the production obtained with Gisela 5 rootstock, and it does not exhibit any chlorotic symptoms.

Almond seedlings, traditionally used as rootstocks in arid and semi-arid regions, have shown promising performance in calcareous soils under limited rainfall conditions. The almond × peach hybrid Monegro rootstock is mainly selected for almonds in non-irrigated conditions and showed high resistance to water stress, good vigour, easy clonal propagation and graft compatibility with the whole range of peach and almond cultivars, as well as some plum and apricot [9]. Moreover, the Supernova, Texas, Marcona, Shokoufeh and K13-40 cultivars grafted on the GF677 rootstock (peach × almond hybrid) demonstrated significantly higher resistance to drought stress compared to the same cultivars on the GN22 (peach × almond hybrid) and No. 32 (bitter almond seedling) [9].

Agroforestry

Agroforestry is an ancestral farming system where different crops (perennial and annual) and, frequently, livestock (sylvo-pastoralism) are grown together in a structured system. It was quite common in the Mediterranean Basin and is often referred to as Mediterranean polyculture. Nowadays, agroforestry has been elaborated into modern agriculture, and the result is a set of practices that enhances and makes use of the synergy between different plant species and between plants and animals.

The most common form of agroforestry still in use is applied to olive groves, where either other crops are grown under the trees (vegetables, small cereals) or animals are reared (often sheep or poultry) under the trees, with mutually beneficial effects, mainly linked to shading and formation of a better microclimate.

Agroforestry can be applied to viticulture, too, leading to changes in vine plant microclimate: i) the shade of the trees affects the radiation received by the vine; ii) the trees also change the air circulation, which can contribute to increased turbulent flows and lead to a decrease in summer temperature peaks, as well as a reduction in the duration of foliar humectation; iii) deep water resources are recycled into the atmosphere, resulting in increased relative humidity and cooling of the air [10].

PROTECTING CROPS FROM HAILSTORMS

Hailstorms can cause physical damage to plants, leading to reduced yields and lower product quality. On a global scale, hail events have reportedly risen in the last decades, although some insurance solutions are available. The impact of hailstorms can be mitigated by hail nets, cloud physics weather modification technology (cloud seeding) [11] and early warning systems.

Protective nets

Hail protection nets are deployed in vineyards and orchards to protect vegetative parts from hailstorms. Nets can be made from various materials – polypropylene for the most part or starch for biodegradable nets, which are rarer due to their cost and shorter lifespan. Nets are estimated to have a lifespan of around 10 years, but this can vary according to their structure, composition and hail events experienced.

In viticulture, the most effective system is to lay the netting flat over the rows, providing total coverage and making use of the existing trellising system or, better yet, configuring it at planting. This system is best suited to wide vines (3 m or more), as it must be possible to open the netting to dump the hail that has accumulated between the rows if it is too heavy. This system allows manual and mechanical work in the vineyard but requires a heavy installation infrastructure that has an aesthetic impact. The investment is substantial, about €20,000–€25,000 per hectare (3-m row spacing). In France, this system is not authorised for wines with a geographical indication and is generally reserved for table grapes. For vines with row spacing less than 3 m, single-row or row-by-row nets are more suitable. Anti-hail nets have a mesh (5x5 mm or 7x3 mm square mesh, depending on the model) designed to prevent hailstones from reaching the foliage and bunches. They are manufactured from extruded polypropylene or woven polyethylene and possibly reinforced with braided wires [12].

Hail cannons

Hail cannons create shock waves that melt the ice particles in the clouds, physically impeding hail formation and growth (Fig. 10). Contemporary hail cannons, which direct blasts of sound at high volumes (≥120 dB) upward using butane gas or acetylene, are actively used in agricultural areas in Italy, France, Spain, Austria, the Netherlands, the USA, Australia, New Zealand and China. As the shock waves do not affect hail that has already formed, hail cannons must be activated 20 min before the formation of hail clouds. Hail-tracking devices, such as Doppler radar, are recommended to ensure the effectiveness of hail cannons.

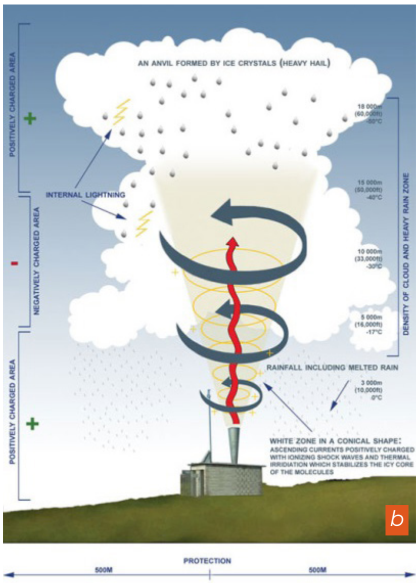

Fig. 7. a) Hail cannon [13] and b) operational diagram [14]

PREVENTING DAMAGE FROM SPRING FROST

The warming produced by global climate change, particularly in the Mediterranean area, has resulted in alterations in plant phenology. Several studies have demonstrated a shift in the timing of phenological events, with 78% of all flowering and fruiting events occurring earlier (30% significantly), increasing the risk of frost exposure for developing flowers and freshly set fruits, which are also particularly susceptible to cold temperatures. This risk is expected to increase, especially at elevations above 800 m, due to earlier flowering [15]. Furthermore, autumn frosts can also cause significant damage, especially to plants that have not yet entered dormancy. Frost damage results in important production losses for the agricultural sector. The Combined Agrarian Insurance evaluated the production losses in Spain at €60 million (2018). To enhance resilience to frost hazards in the Mediterranean region, a comprehensive approach is required that combines agricultural practices, protective measures, technological advancements and community engagement.

Existing frost control methods

Some techniques are available for preventing frost damage in several crops, such as air circulation, fixed or mobile anti-freeze towers, helicopters, cold air extraction, heating systems, dynamic hot air transfer and water sprinkling (Fig. 8, 9, 10). These techniques increase the temperature around the plant with variable thermal gain (up to 4°C) and cost. [13, 16, 17, 18]

Fig. 8. Over-plant traditional sprinkling and sprinklers [19]

Fig. 9. Under-tree microsprinkling and microsprinklers [19]

Fig. 10. Fans for protection from spring frost [19]

SOLUTION AVAILABLE ON THE MARKET: USING RISK-FORECASTING DECISION-SUPPORT SOLUTIONS[2]

An example of one such product that can be used, identified through CLIMED-FRUIT's Open Contest, collecting existing solutions on the market from providers, is Vintel®, a comprehensive software program that includes all of a vine's crop management practices. It provides strategic and operational decisions based on forecasting and risk management, all aimed at achieving sustainable vineyard performance. Vintel® includes frost risk forecasting, simulation of yield loss and protection measure effectiveness, making it a robust solution for vineyard management.

2. Vintel is one of the winning technologies/products from the Crowd-Writing Contest organised by Climed-Fruit in 2023, aimed at private companies, to make mainstream farmers aware of the most recent innovations that promote resilience to climate change. See all winning technologies here.

Farming practices

To effectively manage frost hazards, farmers can adopt a variety of proactive practices to minimize the risk of frost damage and enhance resilience.

Late winter pruning: example in viticulture

In vine growing, adopting late winter pruning – a cheap technique – has the potential to delay budburst and, in certain instances, grape ripening. This technique was implemented in Italy by OG VIRECLI and represents a strategy against spring frost.

This technique is implemented at the winter pruning stage and is an adaptation of regular winter pruning based on grape acrotony. It consists of the following steps:

- perform a pre-pruning operation to optimise the organisation of the pruning steps (reducing the time needed for pruning): the shoots must be long and kept upright (Fig.11). This operation will help to get through the spring frost stage; however, it might not always have an impact on ripening delay at harvest time;
- perform the pruning step to remove the correct leaf area, which is not more than two unfolded leaves on the apical shoots, so the buds located in the basal position are thereby protected in case of spring frosts (Fig. 12). It is crucial to remove the correct leaf surface area; if the operation is performed at a later point, it will cause a yield loss (Fig. 13).

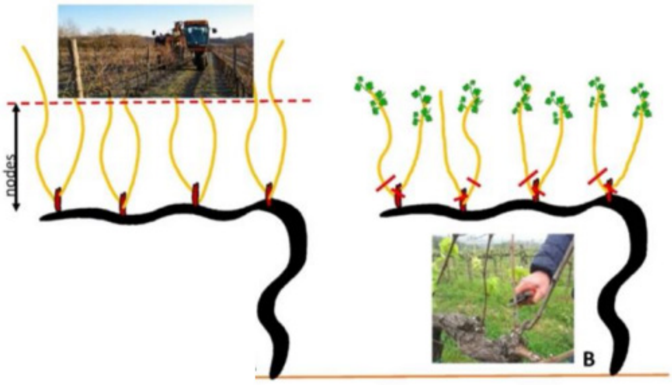

Fig. 11. Late winter pruning in two steps – OG VIRECLI

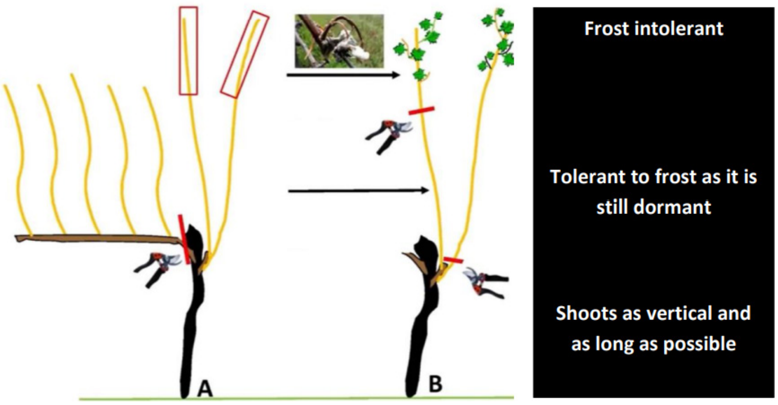

Fig. 12. Bud frost tolerance versus bud position on the shoots OG VIRECLI

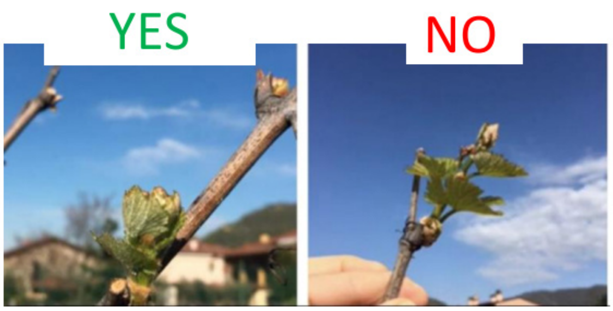

Fig. 13. Right way to perform late pruning – OG VIRECLI

Soil management practices

The SICTAG EU project focused on avoiding the increasing frost risks in French vineyards through soil management practices. It was observed that unploughed soil in vineyards significantly decreased the humidity near the buds – by 33% compared to ploughed vineyards (Fig. 14, 15). Higher humidity increases the damage caused by frost to the buds: at the same temperature, 20% more humidity leads to a 50% increase in bud damage. It was concluded that if frost is forecast, the atmosphere around the buds needs to be as dry as possible by avoiding tillage or mowing practices five to six days before the frost event. The volume of soil moved also impacts the number of days it takes to reach the same humidity around the buds as in the case of untilled soils.

Fig. 14. Sensors monitoring humidity and temperature near the buds in three different soil management treatments – SICTAG EU

Agroclimatic map for anticipating the planting of avocados in Spain

Avocado is a new crop in Europe, and many farmers are planting it due to its better economic profitability and the new climatic conditions. However, avocado trees are considered sensitive to frost and farmers are unfamiliar with the appropriate agronomic techniques to adapt them to specific conditions. It is necessary to identify whether the conditions are suitable before opting for this crop. Therefore, a regional agroclimatic map has been drawn up by the OG GO AVOCADO to identify the plots that meet the optimal conditions (Fig. 16). These conditions were defined by Calatrava (1993) and used in the OG GO AVOCADO to define zones recommended for avocado cultivation:

- Optimum: minimum temperatures below 0°C once every 10 years and never below -2°C
- Viable: absolute minimum temperatures below -2°C but never below -4°C
- Potential: absolute minimum temperatures below -4°C once every 10 years
- Unsuitable: all others

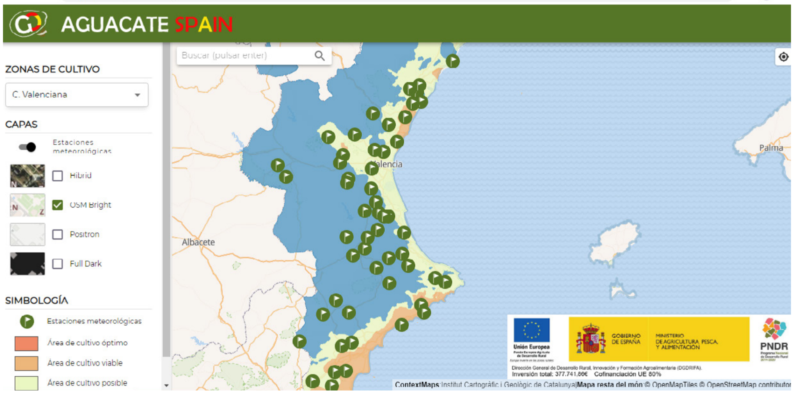

Fig. 16. Agroclimatic map – OG GO AVOCADO

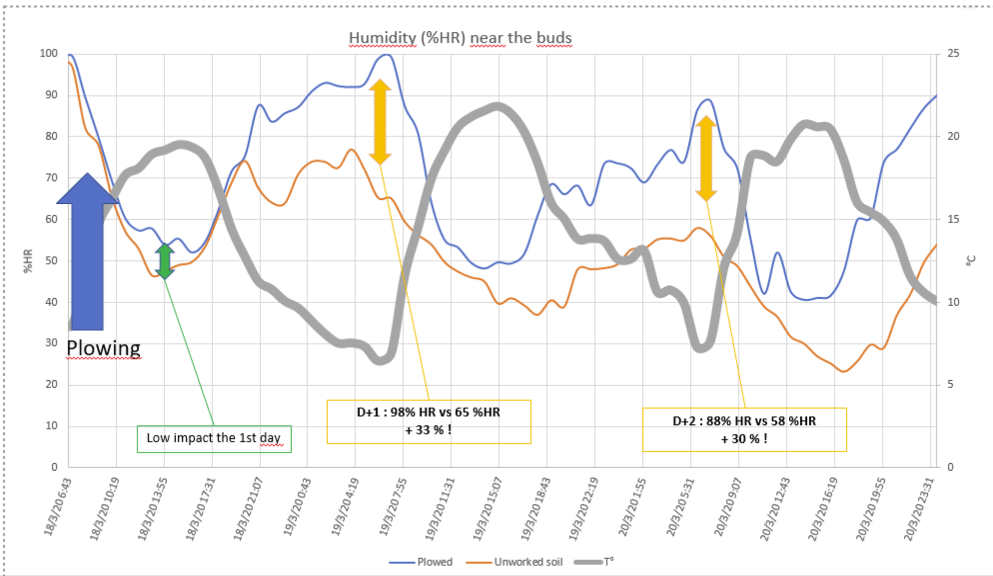

Fig. 15. Effect of soil management on humidity variation near the buds – SICTAG EU

Variety/rootstock choice

In the natural environment, a diversity of plant species, including vines, exhibit varying levels of sensitivity to climatic conditions. Some varieties demonstrate reduced sensitivity to frosts during their early developmental stages. Choosing a later variety (i.e., the buds come out later or late-blooming) represents a potential strategy for mitigating the impact of frost. It is, therefore, recommended to consider variety phenology as a parameter for future planting. For example, in almond cultivation, late cultivars can be planted as late Antoñeta, Marta, extra-late Penta, Makako and Tardona (CEBAS-CSIC), late Guara, Felisia, Belona, Soleta and extra-late Vialfas, Mardía (CITA of Aragón). However, it is crucial to exercise caution when cultivating extra-late and ultra-late flowering varieties with high chilling requirements in regions with a very warm climate, as it may not be possible to reach the chilling temperatures needed to break dormancy.

PREVENTING SOIL EROSION

In recent years, soil erosion has increased notably in the Mediterranean region, attributable to irregular rainfall and droughts, unsustainable farming practices, deforestation and urbanisation. The region's steep topography further exacerbates erosion, leading to significant soil loss and degradation. This process has major agricultural consequences, particularly for perennial crops, which are central to the Mediterranean economy. Erosion has a detrimental impact on soil quality, reducing water retention and damaging soil structure. This severely affects crop yields and long-term sustainability. Various adaptation measures are being implemented to address this challenge, including sustainable land management, vegetative cover, conservation tillage and improved irrigation techniques. These strategies aim to reduce soil loss, restore soil health, and enhance the resilience of Mediterranean agricultural systems.

Implementing plant cover

Vegetation cover and grass cover in perennial crops are a fully-fledged tool in the fight against erosion. Trials carried out in Spanish vineyards through the VITISAD PROJECT have shown that grass cover reduced erosion by 64% compared to ploughed soil.

The OG GASCOGN'INNOV aimed to acquire technical knowledge about the impact of viticultural practices on soil biology in France. The use of green manure has been studied in this context. Green manure is a cover crop with a high rate of leguminous species that produces biomass that is returned to the soil to improve its fertility and structure. This cover crop has many advantages beyond just reducing erosion. In the Mediterranean context, sowing as early as possible (late August–early September) will ensure that the seedlings are well-developed during heavy rainfall in autumn to reduce erosion and prevent vine leaves from flying away (an additional source of nutrition for the soil).

Furthermore, the OG CARBOCERT applied permanent cover with spontaneous crops in alleys, rows and slopes on almond plantations in Spain, mainly to enhance soil carbon sequestration. This practice contributed significantly to controlling soil erosion and runoff. The vegetation influences erosion mainly by intercepting rainfall and protecting the soil surface against the impact of rainfall drops.

Conservation tillage

Minimum soil treatment with appropriate soil management tools minimises soil erosion and compaction. Soil labour should not go deeper than 15 cm, using appropriate tools, such as a cultivator or a disc harrow. Soil management must be minimal and with no change of soil layers (as happens with ploughing) to minimise the environmental footprint and adapt to each soil type's features and plot configuration. Minimal soil treatment results in minimised soil erosion, especially in sloping soils, avoiding the loss of valuable surface soil.

COPING WITH EMERGING PESTS

In recent years, the Mediterranean region has experienced a significant rise in the spread of new pests and diseases, posing a severe threat to its main perennial crops. This increase is largely driven by climate change, globalisation and changing agricultural practices, which have created favourable conditions for introducing and spreading invasive species and pathogens. These new threats are jeopardising the economic stability of agricultural producers and impacting global markets. Addressing this growing crisis requires enhanced surveillance, research into resistant crop varieties and the development of integrated pest and disease management strategies across the Mediterranean region.

It is important to distinguish between emerging threats to perennial crops that cause direct and indirect damage: 'direct damage' typically refers to damage caused by an insect's physical action (trophic or oviposition), while 'indirect damage' refers, for example, to the transmission of pathogens through insects, known as vector-borne disease. [20]

Direct damage

Popilia japonica

The Japanese beetle, *Popilia japonica*, is an invasive pest introduced to eastern North America from Japan in 1916. This insect can cause significant damage to ornamental plants, fruit and vegetable gardens, nurseries, orchards and crops. *Popillia japonica* was first detected in Europe in 2014, in northern Italy (Piedmont and Lombardy). The beetle colonizes the aerial parts of plants and devours the tissue between the leaf veins, leaving only a lacy leaf skeleton (Fig. 17). At the larva stage, it mainly infests the roots of grasses.

Phytosanitary measures are available to reduce the likelihood of introducing *Popillia japonica*, such as early detection with traps, delimitation of risk zones (meadows, football pitches, etc.) and, in case of infestation, the use of attract-and-kill devices, while pesticides may be used in combination with cultural practices (reducing irrigation during the egg-laying period or ploughing the soil in autumn); the possibility of importing parasitoids and other biological control agents from the native area of *P. japonica* is currently under investigation. [21, 22]

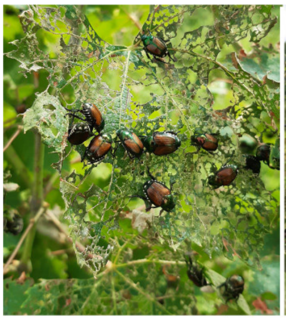

Fig. 17. Damage caused by adult Popillia japonica in vineyards [21]

Grape leafhopper

The grape leafhopper is a common pest in viticulture worldwide. It is causing severe damage in Mediterranean vineyards due mainly to climate change (Fig. 18). Cooperation Projects Generalitat Valenciana implemented an integrated pest management (IPM) strategy through three actions: i) identifying the pest species, ii) evaluating the effect of the grape leafhopper in the region of Valencia, Spain and iii) discussing the different pest management strategies. In the project, 10 vineyards in the region of Valencia were monitored using yellow sticky traps and insect aspiration, and DNA extractions were carried out to identify leafhopper species. Before harvest, leaf damage was evaluated through image analysis. The results confirm the presence of the pest mainly between July and September. *Jacobiasca lybica*, *Empoasca vitis* and *Asymmetrasca decedens* are the main leafhoppers identified. Although treatments with the insecticide acetamiprid help to control the pest, they can create resistance, which, in turn, can reduce the treatments' efficacy, as experienced in a vineyard in Novelda. Kaolin at 3% was an effective way to control the pest (Fig. 19), reducing pest damage by more than 30%, and it could be an interesting alternative to chemical treatments, with no impact on beneficial insects and no risk of generating resistance.

Fig. 18. Leafhopper damage in the Forcallà variety [23]

Fig. 19. Kaolin treatments [23]

Indirect damage

The example of Xylella fastidiosa

Xylella fastidiosa (XF) has been spread in the Mediterranean area in recent years. XF is a xylem bacterium that infects more than 600 plant species and spreads in plant communities through xylem-feeding hemipteran insect vectors. XF causes devastating diseases with a high economic impact in some plant species, such as grapevine, peach and citrus species, which suffer, respectively, from the so-called Pierce's disease (PD), phony peach disease (PPD) and citrus variegated chlorosis (CVC). Since October 2013, XF has been infesting olive groves (*Olea europea* L.) in Salento (Apulia, Italy), causing severe twig and branch dieback due to olive quick decline syndrome (OQDS), which is destroying millions of olive trees.

In a vineyard, the accumulation of XF bacterium gradually clogs the vine, limiting the circulation of sap. This results in yellowing or partial reddening and drying of the leaves. There are shoot lignification defects, with leaf blade abscises, and the petiole (leave stem) remains attached to the shoot. The vine is no longer fed. It dries out and generally dies after one or two years. [24]

In citrus, XF induces leaf necrosis; plant development is subsequently curtailed (dieback), but the plant does not die, although there is a reduction in both weight and the number of fruits. [25]

In olive groves, the XF bacterium is responsible for a severe disease OQDS characterized by the scorching of leaves and scattered desiccation of branches and twigs. These symptoms usually start at the top of the olive canopy and expand to the rest of the crown, ultimately causing the death of the trees (Fig. 20). [26]

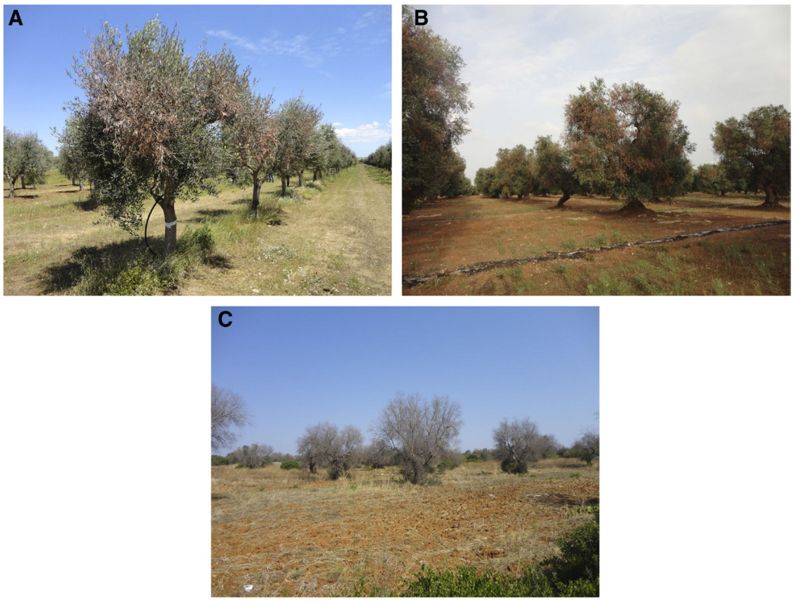

Fig. 20. A) Young and B) centenary olive trees with canopies showing manifest branch desiccations induced by XF. C) Olive orchard at advanced stage of disease with whole trees dead. [27]

The XF bacterium is a priority quarantine organism within the EU. Unfortunately, there are currently no curative measures to combat the bacterium. The severity of this situation is underscored by European regulation (2020/1201/EU), which recommends uprooting and destroying contaminated plants as the primary preventive action.[28]

Farmers must adopt vigilance and aggressive management strategies: i) plant certified, disease-free plants; ii) disinfect pruning tools with a bleach solution; iii) remove and discard infected plants.

More information on emerging threats in Europe: POnTE project, XF Actor project and EIP-AGRI Focus Group on diseases and pests in viticulture

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SUBTOPIC 3:
INNOVATIVE PRACTICES FOR WATER STRESS MANAGEMENT AND DRY FARMING

Water scarcity is a defining feature of the Mediterranean climate and is further aggravated by the impacts of climate change, including increased evapotranspiration, reduced rainfall and prolonged droughts. As agriculture remains the largest water user in the region, adapting irrigation and crop management practices is essential to ensure productivity and sustainability.

This chapter reviews innovative water management strategies and dry farming techniques designed to reduce water use and improve plant resilience under limited water conditions, drawing on examples from the CLIMED-FRUIT project and other regional initiatives.Advanced irrigation techniques

ADVANCED IRRIGATION TECHNIQUES

Setting up a traditional water-efficient irrigation system

There are various ways of improving irrigation water efficiency. Firstly, the choice of irrigation system is a critical factor: choosing a localised drip or 'micro-jet' system distributes water as close as possible to the roots, avoiding excessive evaporation and limiting the development of weeds. However, very localised water distribution does not stimulate the development of root systems in terms of either their depth or across a large horizontal area, thus increasing the plants' dependence on irrigation. Therefore, the choice of irrigation system, its positioning and the timing of inputs are all factors that go into improving water use efficiency.

Drip irrigation

Drip irrigation is one of the most widespread systems for growing perennial crops (Fig. 1). In this system, a reduced quantity of water is applied to the roots of plants in the form of continuous or discrete drops, tiny streams or pulse systems. Between 2 and 20 liters are delivered per hour from a narrow tube with several orifices known as emitters [1]. Drip irrigation is widely known to increase water use efficiency by having 50% less water demand than furrow irrigation and reducing waterlogging.

Fig. 1. Aerial drip irrigation system in viticulture (photo credit: IFV Sud-Ouest)

Deficit irrigation

Deficit irrigation (DI) is a watering strategy where irrigation is only applied during drought-sensitive crop growth stages to reduce water wastage.

There are different types of DI (Fig. 2):

- **Sustained DI:** based on distributing the water deficit uniformly over the whole fruit season, thus avoiding the occurrence of a severe plant water deficit at any crop stage that might affect the marketable yield or fruit quality.
- **Regulated DI:** full irrigation is supplied during fruit trees' critical periods, while it is limited or even unnecessary if a minimum supply of water is provided by rainfall during critical periods.
- **Partial root drying DI:** based on irrigating only one part of the root zone, leaving another part to dry to a certain soil water content before rewetting by shifting irrigation to the dry side.

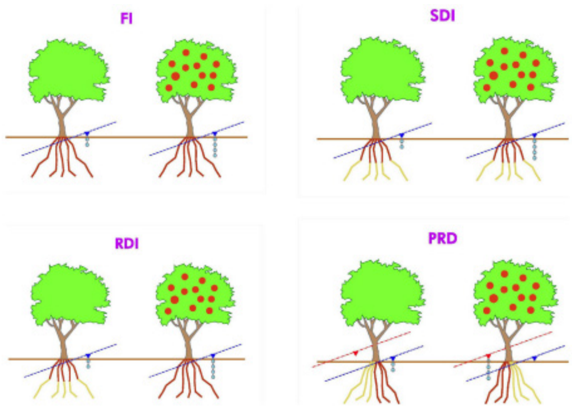

Fig. 2. Graphic pattern of full irrigation (FI), sustained deficit irrigation (SDI), regulated deficit irrigation (RDI) and partial root drying (PRD) strategies in fruit trees [2]

DI in a pistachio orchard

Despite good pistachio crop performance under dryland conditions, there is a clear tendency to irrigate due to the benefits in terms of fruit quality and crop productivity. The response to regulated deficit irrigation (RDI) has been studied in a pistachio orchard (Kerman variety) in Ciudad Real (Spain), concluding that the application of RDI at 15% of crop evapotranspiration (ETc) during the increase of kernel weight (stage III - final stage of fruit growth) results in a higher fruit size than when the same amount of irrigation water is distributed in earlier stages [3].

Furthermore, RDI at 50% ETc at stages I (rapid nut growth) and II (nut hardening) provided a similar total yield and percentage of split nuts as fully irrigated trees, as well as allowing water savings of 20% [4]. These examples illustrate that deficit irrigation is a possible strategy for reducing water consumption without significantly impacting the yield.

DI in cherry orchards

The agronomic response of sweet cherry 'Prime Giant' involving DI strategies in a semi-arid Mediterranean climate was studied in a commercial orchard in southeastern Spain (Jumilla, Spain). The RDI treatment, irrigated at 100% ETc during pre-harvest and floral differentiation and at 55% ETc during post-harvest, reduced vegetative growth over four years without penalising total fruit yield or quality, particularly fruit size. This treatment allowed water savings of 39% compared to the control treatment without restriction w[5]. Moreover, RDI led to a significantly lower incidence of fruit cracking and a lower cracking index, which could extend fruit shelf life.

The same finding was reported with post-harvest application of partial deficit irrigation (PDI) of 30% and 50% over three years in cherry 'Sweetheart' in the Okanagan Valley (southern British Columbia, Canada). The water reduction had no lasting effects on the trees' water status, photosynthesis rates or plant growth [5]. PDI did not impact fruit yield, quality at harvest or after storage and shelf-life conditions, either [6]. These findings suggest that RDI and PDI treatments in cherry orchards can significantly reduce irrigation water use without compromising fruit production or quality.

DI in an almond orchard

Moreover, the effects of regulated deficit irrigation (RDI) were assessed in Morocco in terms of reducing the adverse effects of water stress on the performance of almond 'Tuono'. Irrigation treatments consisted of RDI at 75% ETc and 50% ETc applied during fruit growth slowdown periods corresponding to stages II (pit hardening) and III (final stage of fruit growth) in almonds (Fig.3). It was reported that water was saved by up to 50% during the fruit growth slowdown period, with improvements in fruit quality without decreasing total yield [7]. Almonds generated under deficit irrigation conditions are called 'hydroSOStainable', indicating that they are environmentally friendly and water-saving products with higher nutritional, functional and sensory quality. This concept was developed in Spain and has been registered with the Spanish Patent and Trademark Office since 2017 [8]. Research on how this information influenced Spanish and Polish consumers' taste and preference for roasting almonds labelled as 'hydroSOStainable' and 'conventional', using satisfaction degree and willingness to pay questions, revealed that 77% of these consumers were willing to pay a higher price for the almonds labelled 'hydroSOStainable'[8].

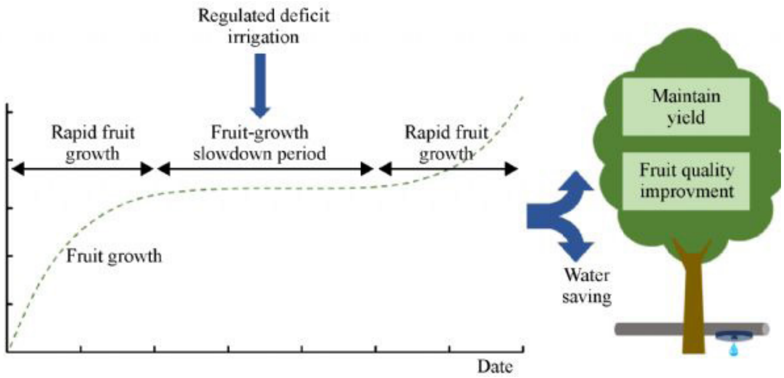

Fig. 3. Graphical abstract of the application of RDI [7]

DI in an olive orchard

DI has also been applied for three years in a young super high-density olive orchard (Arbequina cultivar) in northeastern Spain [9]. The RDI strategy (50% Etc) applied during summer vegetative growth produced promising results based on a water-saving rate of 19% without affecting olive weight at harvest or oil yield. Moreover, in a 17-year-old, low-density 'Koroneiki' orchard in Cyprus, applying RDI of 70% ETc during water-stress sensitive growth stages (shoot growth, flowering and bud initiation) and 35% ETc during water-stress tolerant growth stages (pit hardening, oil accumulation), resulted in irrigation water savings of 32% without affecting olive or oil yield and quality [10].

Subsurface irrigation

The French Operational Group (OG) OFIVO examined the effect of aerial drip and subsurface drip irrigation in a vineyard using soil capacitive probes (wet bulbs, Fig. 4). The application of subsurface irrigation (40 cm depth) in the middle of the row generated larger wet bulb volumes (with vertical and lateral percolation of the water) than the aerial drip irrigation system (Fig. 5). In subsurface irrigation, water reaches the ground surface by capillarity without changing the vines' water status or the yields compared to aerial irrigation.

Fig. 4. Use of capacitive probe to study water behaviour in the soil – OG OFIVO

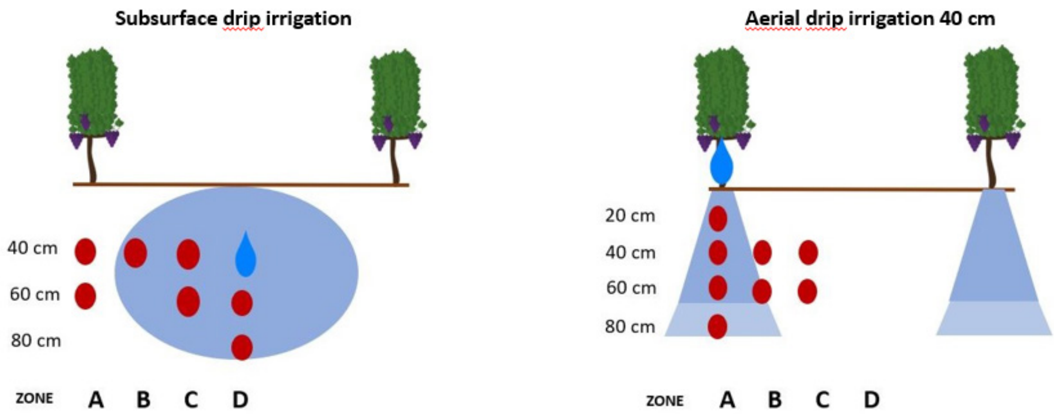

Fig. 5. Capacitive probe positioning in subsurface irrigation and aerial irrigation treatments [11]

Subsurface dripper irrigation facilitates mechanical weeding/weed management and improves root expansion between rows. The main benefit of this irrigation system in the Mediterranean area is water use efficiency, facilitating the establishment of vegetal cover and maintaining viticulture in dry areas. However, this system is more expensive to install than an aerial drip system (+20%) and unsuitable for stony soils. Moreover, the full fertigation strategy was applied, which showed the best ratio between yield and maturity. It significantly reduced inputs (30% fewer fertilisers). The system's end-of-life must also be considered, and soil contamination with plastic residues must be avoided.

Smart irrigation systems

Wine vineyard

In northern Italy, the OG VIRECLI applied a precision irrigation system to maintain production and quality standards in grapes used to produce sparkling wine, even in the most challenging vintages. By optimising water use, they achieved higher production with superior quality characteristics compared to on-farm management and non-irrigated systems, despite severe drought. The results were particularly significant in vineyard plots with higher water requirements.

A thorough analysis of soil characteristics and their variability within the vineyard is needed for proper irrigation system design. This can be done using state-of-the-art technologies such as those based on acquiring electrical resistivity and strongly correlated with the main soil physicochemical parameters. The indications thus obtained make it possible to divide the vineyard into homogeneous zones, within which the hydrological properties are uniform. Each homogeneous zone is finally characterised through the soil data obtained from the survey that results in a vigour map (Fig. 6). Based on the information gathered, the pitch of the drippers varies within the vineyard to meet the water needs of the defined homogeneous management zones (Fig. 7). It is necessary to use a decision support system (DSS) to guide the irrigation (i.e., a DSS that considers soil water content and plant needs, together with meteorological forecast) to identify the best time to irrigate; the systems tested were Irriframe ANBI, based on a classical water balance, and Manna by Rivulis, integrated with satellite data. Both systems were appropriately calibrated with on-site measurements of the plant's actual water status.

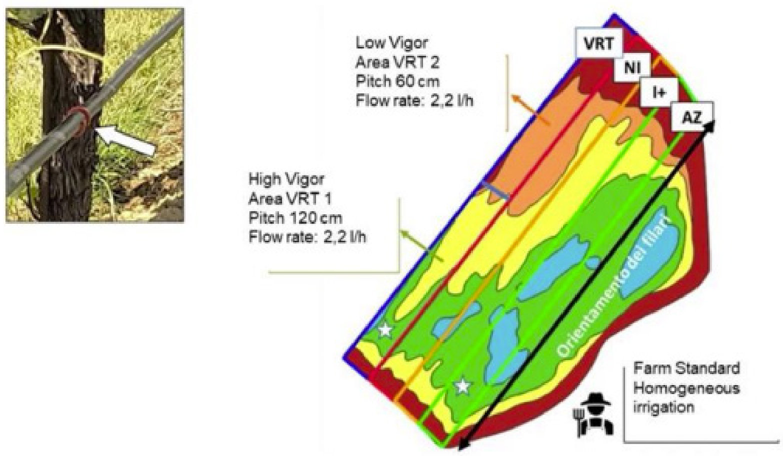

Fig 6. Example of distribution of different irrigation theses and characteristics of a variable rate irrigation system – OG VIRECLI

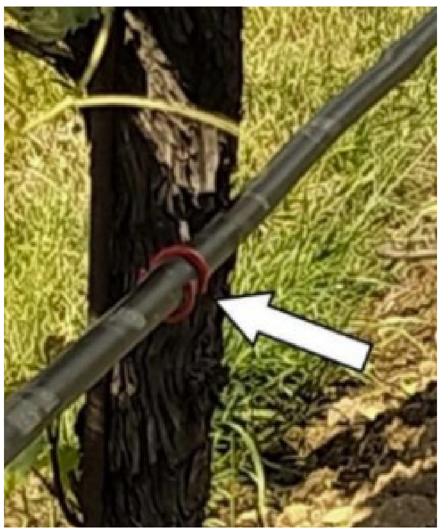

Fig. 7. Hydro clips applied to the drippers to close them and modulate the pitch and obtain a variable-rate drip system – OG VIRECLI

Table grape vineyard

The water consumption of a 2-ha table grape vineyard in the Apulia region (southern Italy) can range from 2,000 to 6,000 L per season, depending on the irrigation technique applied and the specific needs of variety, emphasising the importance of resource use efficiency. The OG OLTREBIO implemented interconnected sensors at soil and crop levels on a farm (Fig. 8), which communicated with the decision support system (DSS) for water management in organic table grape vineyards to optimise resources. Water use is registered and managed on a seasonal basis with the help of IoT sensors at various levels (soil and crop) using locally obtained weather data (Fig. 9.). Data is gathered in Blueleaf® software. The DSS system, a key component, is tailored to the table grape vineyard and plays a crucial role in managing water use during critical periods of water scarcity. The benefit for DSS users is the efficient use of water resources, saving water by approximately 30% to 40% depending on the seasonal trends and the grower's work time, without compromising crop production or fruit quality.

Fig. 8. Sensors at soil and crop levels – OG OLTREBIO

Fig. 9. Communication method between the hardware and software – OG OLTREBIO

Avocado orchard

Due to the better economic profitability of avocado and the new climatic conditions, European farmers are turning to it as a substitute for other crops. Avocado is sensitive to drought and root asphyxia, requiring an exact water volume to grow and produce fruit. The shallow roots limit the ability to exploit large volumes of soil and fully use stored rainfall. Many farmers need to familiarise themselves with the most appropriate agronomic techniques adapted to the specific conditions. In this context, OG GO AVOCADO has been leading in the development of new cultivation practices, such as using capacitance probes (Fig. 10) combined with drones and agroclimatic maps (Fig. 11). Before planting, the agroclimatic map must be consulted to determine whether the plot meets the optimum conditions. At the same time, a suitable irrigation system is essential for water efficiency, regardless of the plot location. Capacitance probes can be chosen to determine the irrigation needs at each moment (some are autonomous and work with a small solar panel). These probes can determine soil moisture content, salinity and temperature at different soil depths. The estimation of soil moisture content is based on measuring the soil's electrical constant using electrodes, which can detect oscillations in the constant since the soil is an electrically conductive substrate. These variations in the value of the electrical constant correlate with the soil capacitance or moisture content. The same system is used to estimate soil salinity.

Fig. 10. Capacitance probe on an citrus plantation, similar to the probes used in OG GO AVOCADO

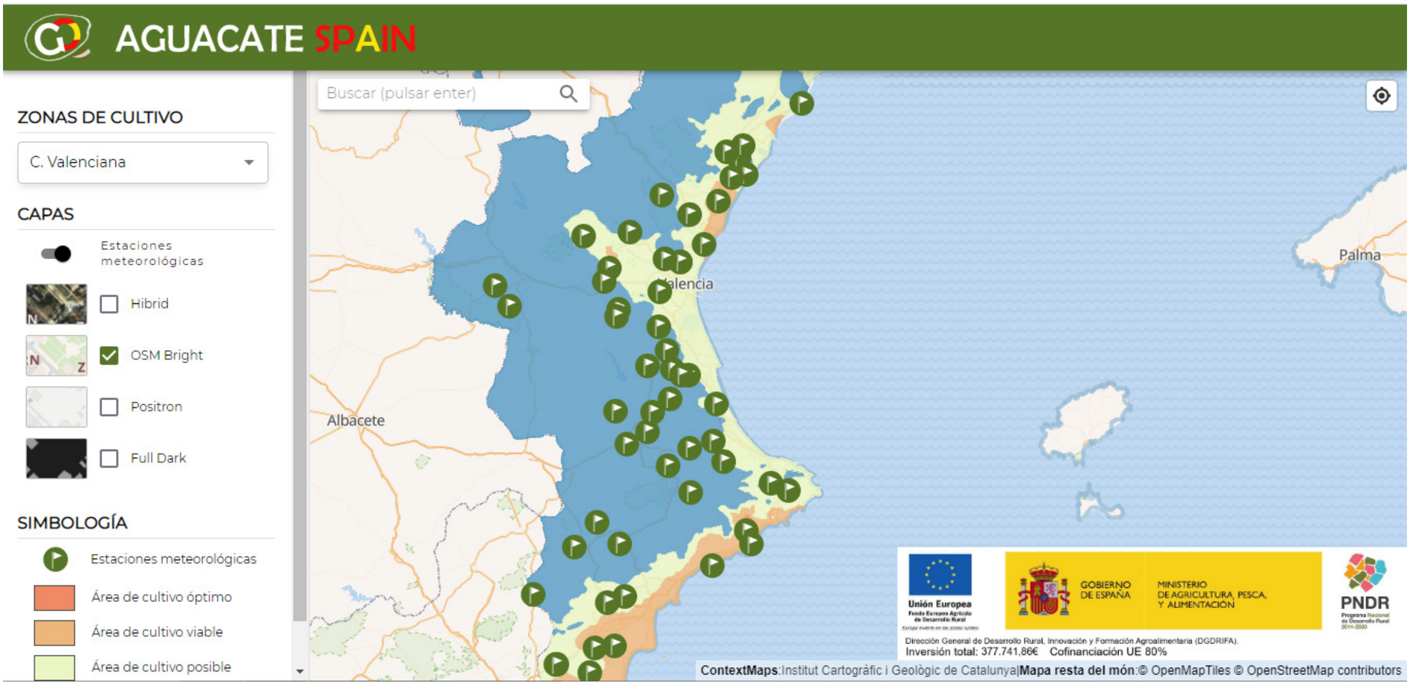

Fig. 11. Agroclimatic map – OG GO AVOCADO

The capacitance probes measure volumetric soil water content (VWC) accurately and in real-time, making it possible to monitor moisture levels in the root zone, detect changes or deviations after irrigations or rainfall and identify drying patterns between irrigations. With this information, the technician can adjust the frequency and duration of irrigations according to the actual needs of the avocado crop. In addition, this avoids excessive irrigation and prevents water stress. Finally, although using capacitance probes for crop water management initially entails an extra cost due to the high price of the technology, it produces significant savings in water, fertiliser and energy by applying only the necessary amounts.

Fig. 12 shows the humidity detected by the probes at four depths (black 10 cm, red 30 cm, blue 50 cm, yellow 70 cm). After each irrigation, the water content of the soil increases to a greater extent in the first centimetres and is practically imperceptible at the deeper levels. The red and black dots show root activity, i.e., the times when the roots take up water.

To determine the exact volume of water needed by the avocado crop, the OG GO AVOCADO monitored instantaneous consumption and adapted the irrigation regime to the real needs of the plant. One hectare of avocado is estimated to consume about 6,300 m^3/year (Manual of practical management of avocado cultivation). This crop needs constant humidification in the root zone, with 50% of the roots located within the first 30 cm of soil. Thus, it was observed that increasing the number of irrigation days but applying a smaller volume of water at each irrigation increased yields compared to irrigating on more days with a higher volume of water. This is because short and continual irrigations keep the soil surface constantly wet. It has been observed that installing ultra-low flow drippers (0.6 l/h) arranged in 4 rows of dripper lines generates constant wetting in the first centimetres of the soil.

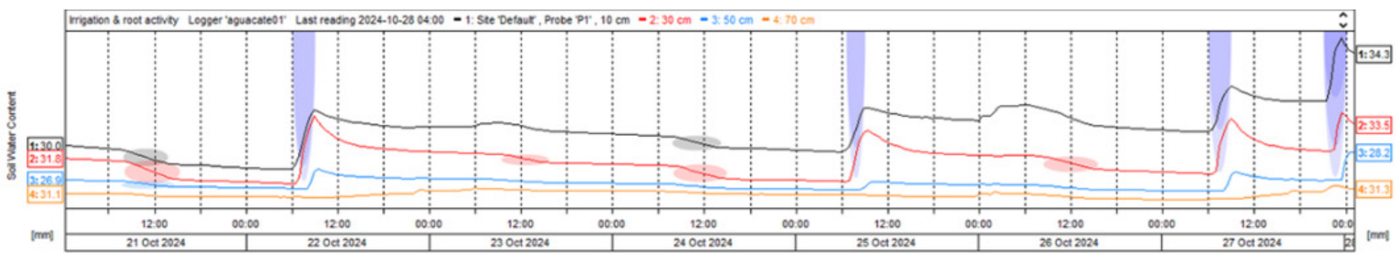

Fig 12. Graph of data from the capacitance probe on the evolution of soil water content at different depths and after irrigations – OG GO AVOCADO

Citrus orchard

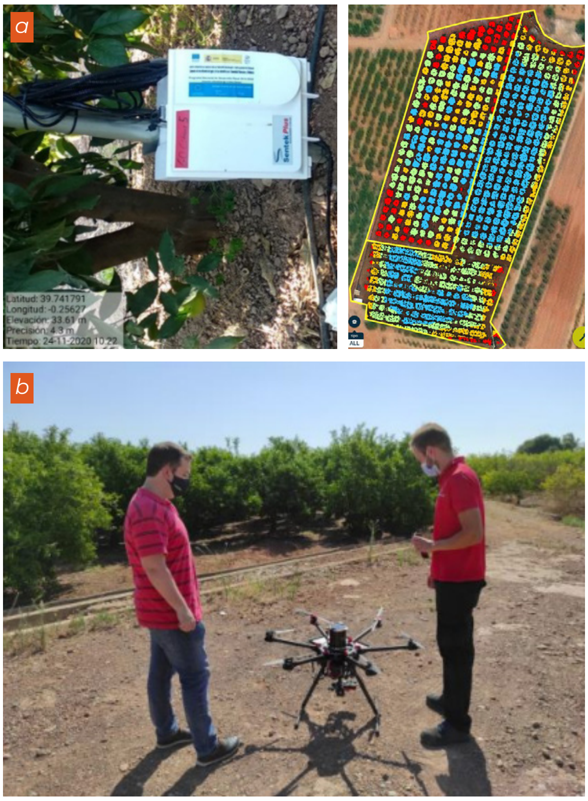

Fig.13 a) Capacitance sensor; b) digital platform with the hydrological results; c) drone equipped with thermographic cameras – OG GO CITRICS

The OG GO CITRICS conducted a pilot test of citrus cultivation using thermographic cameras, drones, satellite information and capacitance sensors to determine the areas with irrigation excesses or deficits to balance this aspect. It was possible to determine the water available in the irrigation system using the data obtained and, by applying the appropriate corrections, the information acquired this way can be transferred to growers for application on their farms. It can be difficult to use this method in some production areas due to the knowledge required to manage these kinds of technology. For this reason, the OG GO CITRICS is working to train farmers to make it easier for them to interpret the valuable information provided by the probes and other monitoring systems. The capacitance probes in the field enable optimal irrigation scheduling based on the optimal time and amount of water needed according to the soil moisture obtained by the sensors (Fig. 13a). In addition, the data obtained from drone flights equipped with a hyperspectral camera (Fig. 13b) and satellite images allowed for detecting failures in the irrigation systems, highlighting areas with both over- and under-irrigation (Fig. 13c). These detections are carried out by monitoring vegetative rates such as the normalised difference vegetation index (NDVI). This parameter is based on detecting infrared wavelengths and provides precious information for preventing crop stresses before the appearance of symptoms in the plant. Stress detection allows for correcting stress early, repairing possible failures and adapting irrigation strategies to crop needs. In addition, a mulch layer of rice straw generates benefits in terms of reducing irrigation requirements by 30% and increasing yield by 10% compared to traditional conditions with 100% ETc irrigation and without mulching.

Almond orchard

Another example of DSS is direct plant sensing, an innovative irrigation planning tool to determine water stress in almonds. This technology is a combination of plant sensors and plant stress algorithms. The trunk of an almond tree shrinks during the day as a response to decreasing water levels. The more it is stressed, the more it contracts before replenishing again at night. The software developed uses this shrink-swell mechanism to quantify water stress [12]. The dendrometer takes the status of the plant automatically every day (Fig. 14), and it is communicated directly to the grower's mobile phone or computer. The software automatically transforms readings into stress alerts and irrigation recommendations with optimal water use.

Fig. 14. Dendrometer

Olive orchard

Precision irrigation based on daily trunk growth using a dendrometer, installed 15 cm above the ground on the main trunk of the trees, was applied for three years in a young super high-density olive orchard (Arbequina cultivar) in northeastern Spain [9]. Based on the dendrometer data, irrigation in July and August (summer vegetative growth stop) occurred after two consecutive days of decreased trunk diameter. The dendrometer took and sent measurements every 15 minutes via radio to a data logger. The olive oil production increased by 7% and the vegetative variables did not show significant reductions, resulting in 31% water savings compared to the control strategy.

DRY FARMING

This type of farming relies on the natural moisture retained in the soil and specific farming techniques to ensure crops receive enough water to grow. However, dry farming requires a high level of skills and experience, as farmers must be able to evaluate the soil status and adapt the techniques to changing weather conditions.

Hydrogels in improving soil water retention

The hillside vineyards in Emilia-Romagna (northern Italy) are increasingly vulnerable to the effects of climate change. Rising temperatures, erratic rainfall and prolonged droughts are putting considerable pressure on traditional viticultural practices. In response to these challenges, the IN+VITE project has explored the use of hydrogels, also known as superabsorbent polymers, to improve water retention in soils and optimise water use in rainfed vineyards. These materials can absorb and retain large quantities of water while gradually releasing it over time. Hydrogels comprise a network of polymer chains with hydrophilic groups that allow them to absorb water up to several hundred times their weight. Recent advances in producing biodegradable variants and reducing manufacturing costs have revived the interest in hydrogels, especially as climate change exacerbates water scarcity. Field trials revealed that adding the hydrogel to sandy soil significantly increased its water-holding capacity. This improvement translates directly into higher water availability for plants, particularly during dry periods, which reduced the need for irrigation and improved growth (Fig. 15) and vine survival, with 6.2% dead vines compared to 15.6% in the control. Furthermore, the hydrogel was applied at planting on a newly planted Sauvignon Blanc vineyard in the Colli Piacentini region. Preliminary results indicated that vines treated with the hydrogel had better water status and more robust growth than those that were not treated. This finding suggests that hydrogels could play a crucial role in successfully establishing new vineyards.

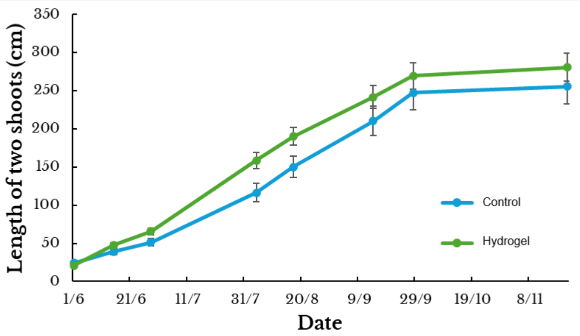

Fig.15. Effect of hydrogel on the length of two shoots on vines – IN+VITE project

Biochar in improving soil water retention

Biochar is created by heating biomass, such as orchard waste or almond shells, at 500°C to 700°C in a process called pyrolysis. The result is a black chalky substance that varies in particle size. Biochar improves nutrient retention thanks to a better cation exchange capacity (CEC), increases water retention in the soil by up to 300% (depending on the type of biochar considered, as its porosity is high), corrects acidity, aerates the soil and develops microbial life (Fig. 16). Biochar is a very stable product; following an application, it can have noticeable effects for up to 10 years, and using it on cropland may reduce irrigation frequency. This is particularly significant in water-scarce or semi-arid areas and sandy soils [13].

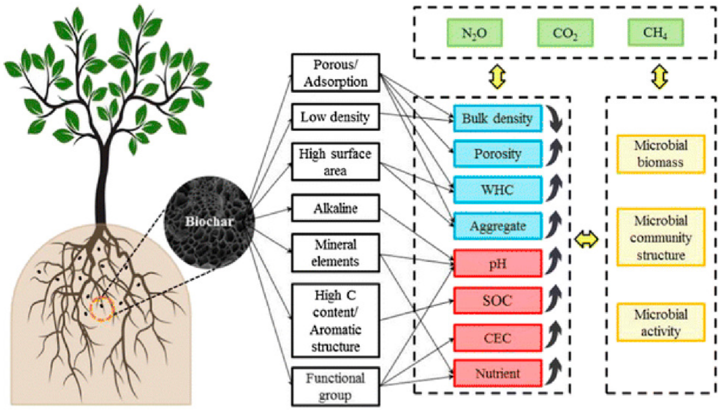

Fig. 16. Effect of biochar on the physical, chemical and hydraulic properties of soil [13]

Soil management practices

Sustainable soil management practices are crucial to preserve soil health and mitigate adverse effects on plant performance. The Portuguese OG New Practices in Rainfed Olive Groves assessed the effects of conventional tillage and self-reseeding annual legume cover crops on plant physiological performance and soil properties. The application of legume cover crops reduced soil erosion risk, improved soil fertility, prevented soil water content loss through evaporation and increased water holding capacity. Therefore, the use of leguminous cover crops is a promising strategy for sustainable soil management in rainfed olive orchards, as it can provide numerous ecosystem services such as nitrogen fixation, hosting beneficials and increasing water retention.

A viticultural experiment conducted in France (VITIMULCH project) showed that the presence of exogenous dead mulches, such as green waste and felts and crushed oysters (Fig. 17), under the row can increase soil humidity up to 20% in a dry vintage (depending on the raw material used, Fig. 18). Furthermore, dead mulches can improve soil structure and physicochemical properties such as pH or organic matter. For example, the annual application of composted green waste under the row (15 cm thick and 60 cm wide) improved organic matter in soil from 1.6% to 4.3% and made it possible to keep 10% more humidity in the soil than in bare soil.

Fig. 17. Vegetal felt under vine raw

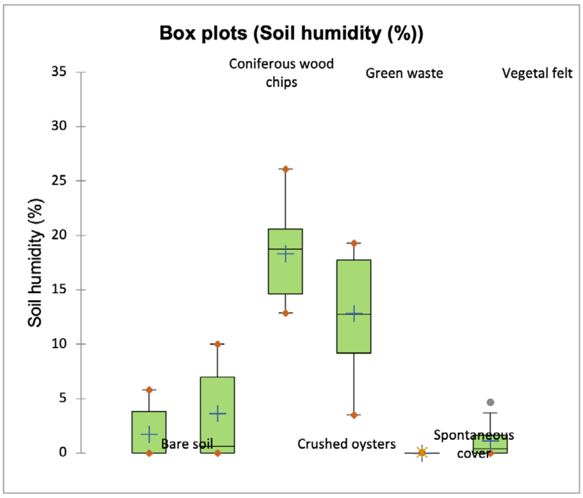

Fig. 18. Soil humidity (%) at 15 cm depth for different exogenous dead mulches under the vine raw, 2023 vintage, Vitimulch project. Bars from left to right: bare soil, crushed oysters, coniferous wood chips, green waste, spontaneous cover, vegetal felt

Keylines

The soil degradation over the last 40 years has caused a decrease of about 30% in the water retention capacity of agricultural soils, compromising their ability to respond to catastrophic weather events [14]. The introduction of tillage techniques along lines, called keylines (Fig. 19), identified along the natural water flows, can make a significant contribution to preventing soil erosion and improving soil water retention capacity.

Keyline design is an agriculture water management system that uses the force of gravity to slow down surface water runoff, intercept it and distribute it slowly away from areas (valleys) with high erosion levels. This is achieved by designing precise cultivation patterns that follow the direction of the keylines upstream and downstream, ensuring consistent water behaviour over the entire slope [15].

Keyline design always starts with a topographical survey (GPS, drone, remote sensing, total station) to obtain a contour map of the area under consideration. Using a contour line for reference, a line called a keyline intersects upstream of the reference curve and crosses the reference curve with a slight slope. A layout representing the cultivation pattern is outlined by drawing the keyline parallel to the upstream and downstream (Fig. 20) flows. In practice, water is thus forced to flow in the direction of the keylines through tillage and cultivation operations (e.g., ripping, harrowing, sowing, harvesting, etc.) for arable crops, aeration for pastures and permanent crops and surface water regulation systems (e.g., ditches).

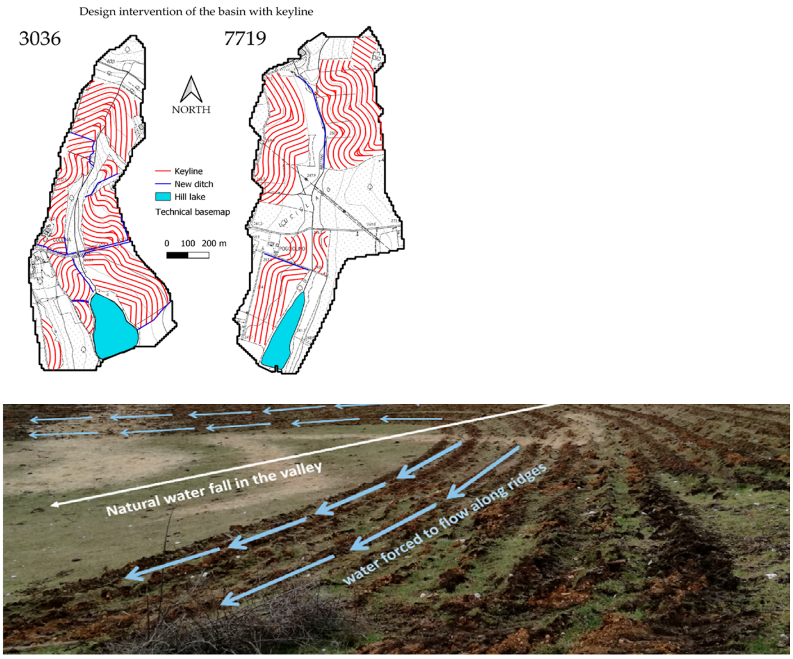

Fig. 20. Arrangement of keylines in arable land (above) and example of tillage following keyline design: a) natural waterfall in the valley; b) water forced to flow along ridges [15]

Fig. 19. Keyline design in the Domaine des Quarres vineyard in Layon, France (photo credit: Domaine des Quarres)

A study in Italy found that keylines significantly impacted runoff distribution and soil moisture in two hydrographic basins in Mugello (Florence) [15]. Introducing keylines with 20-cm deep ditches, placed about 25 m from each other, reduces erosive phenomena between keylines, while outflow follows the keylines. The study also found an increase in the topographic wetness index (TWI) due to the significant outflow in keylines, indicating that topography controls water movement and soil moisture spatial patterns (Fig. 21).

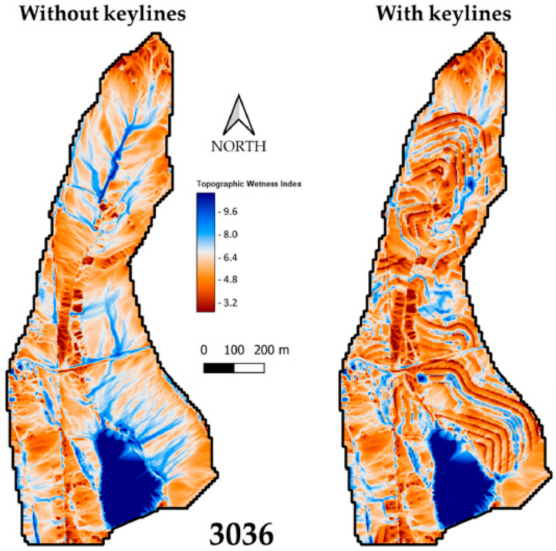

Fig. 21. TWI maps without (a) and with (b) keylines for the same basin [15]

ADAPTATION MEASURES

The agricultural sector is the largest consumer of water in the Mediterranean arid and semi-arid regions, where irrigation water represents 50% to almost 90% of the total water used [16]. Many Mediterranean countries (including Egypt, Libya, Tunisia, Algeria, Morocco, Syria, Malta and Lebanon) exhibit water availability below 1,000 m^3 $person^{-1}$ $year^{-1}$ [17]. Irrigation systems together with advanced technologies and good practices aimed at obtaining complementary resources can increase irrigation efficiency and reduce water wastage.

Desalination

Desalination capacity has increased over the last few decades in the Mediterranean Basin, and the production of desalinated seawater in the Middle East and North Africa region is projected to be thirteen times higher in 2040 than in 2014; Algeria, Egypt, Israel, Italy and Spain are currently the most advanced countries in this regard [18]. Desalination addresses global water scarcity as seawater represents an abundant and stable water source that effectively removes climatological and hydrological constraints. Current desalination technologies include:

- **Membrane technologies:** reverse osmosis (RO) is the most frequently used technique. It consists of filtering water through salt-retaining membranes under high pressure. Electrical dialysis reversal (EDR) is another membrane process where salts are separated from the water by applying an electric potential difference.
- **Thermally driven technologies:** these use heat to evaporate water and subsequently condense it again. Thermally driven technologies include multi-stage flash distillation (MSF), multi-effect distillation (MED), thermal vapour compression (TVC) and mechanical vapour compression (MVC). Membrane distillation (MD) is an emerging hybrid thermal process that uses membranes.

Multi-stage flash distillation and reverse osmosis currently dominate the global desalination market, with the latter being by far the most widely used technology in the EU, accounting for 88.5% of the total capacity [21].

EU facilities can supply up to 3.4 billion m^3 of desalted water annually (active capacity), mainly from seawater and brackish water. About 2178 desalination plants are installed in the EU (Spain 41%, Greece 19%, Italy 18%, Germany 4% and France 3%) [21].

Fig. 22. Geographical distribution of desalination plants in the EU 27, 2024 [19]

One of the main issues limiting the use of desalinated seawater (DSW) in agriculture is its high economic and energy cost compared with other water supplies. Some agronomic concerns need to be considered to avoid unexpected adverse effects. It has been pointed out that the sustainability of the system also requires the correction of several water quality problems, mainly focused on improving DSW quality through desalination techniques to reduce boron (B) levels and on the remineralisation processes to balance cation concentrations and increase pH and alkalinity.

Using renewable energy to power desalination plants is a potential solution for reducing the production cost of DSW. The Canary Islands archipelago (Spain) is a territory with high wind power potential and desalination capacity. Wind energy is connected to desalination plants to reduce the DSW cost. The variable energy cost of the DSW can be reduced by 35% as an annual average [20]. On the other hand, a photovoltaic energy plant was installed at the Mutxamel Seawater Desalination Treatment Plant (SWDTP), located in the region of Alicante on the eastern coast of Spain, to achieve competitive production costs for desalinated water. These facilities reduce energy costs by around 50% and save 20–30% on final water production costs [21].

Water reuse

The volume of wastewater produced in southern and eastern Mediterranean countries was estimated at 81,34 billion m³, making it a valuable water source in terms of quantity [18]. International organisations such as the FAO increasingly encourage wastewater reuse to preserve water resources. In 2010, an estimated 20 million hectares were irrigated with raw or diluted wastewater, meaning around 10% of the irrigated land; only 500,000 hectares are irrigated with treated wastewater. Wastewater reuse rates can reach 90% in arid and semi-arid regions (Israel, Jordan), 25% to 30% in the southern Mediterranean, 14% in Spain and 8% in Italy [22].

In the EU, more than 40 billion m³ of wastewater is treated yearly, but only 2.4% is treated for reuse. While a few countries reclaim almost all their treated wastewater (up to 89%), the majority reclaim only a tiny percentage (as little as 5% in some cases) or do not practice water reuse. This shows considerable potential for making more efficient use of water [22].

Reclaimed wastewater (RWW) is one of the solutions to be developed to meet the challenge of maintaining sustainable access to water, particularly for agriculture and viticulture. RWW aims to supply an additional quantity of water of a quality suitable for a given use without having to wait for it to be purified by a natural cycle.

Water reuse and agricultural irrigation: regulatory framework

The EU Regulation of 25 May 2020 on minimum requirements for water reuse harmonises national regulations and, by simplifying the rules, should facilitate the use of reclaimed wastewater. Targets have been set, 'from 1.7 billion m³ to 6.6 billion m³'. This legislation aims to make the use of treated wastewater to irrigate crops safe, transparent and accessible to farmers. The full text of the regulation is available here: Water Reuse Regulation (Regulation (EU)2020/741).

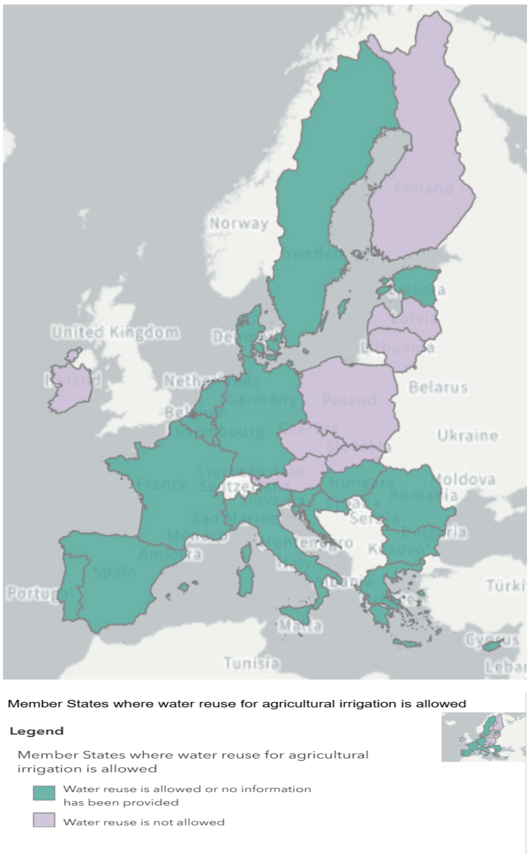

Fig.23. European Member States where water reuse for agricultural irrigation is allowed or not allowed [22] (last update 14 October 2024)

The Water Reuse Regulation is applicable as of 26 June 2023. The Regulation sets out:

- Minimum water quality requirements in the European Union for the safe reuse of treated urban wastewater in agricultural irrigation
- Harmonised minimum monitoring requirements, notably the frequency of monitoring for each water quality parameter and validation monitoring requirements
- Risk management provisions to assess and address potential additional health risks to humans and animals and possible environmental risks
- Permitting requirements for producing and supplying reclaimed water
- Transparency, whereby key information about any water reuse project is made available to the public

The European legislation defines four water quality categories (A, B, C, D) [23] that can be used depending on the crop type (food, processed, industrial) and the water distribution type (with or without contact with the crop). Quality C with drip irrigation is required for vines, depending on the site.

Agronomical impacts

An analysis of the risks associated with water collection and the preventive measures put in place mean that potential pollution problems can now be significantly reduced. The heavy metal fluxes observed at the two pilot stations studied in southern France align with the World Health Organisation recommendations for irrigation water. For example, for zinc and copper, the flow was 100 to 1000 times lower than the standard for spreading sludge from wastewater treatment plants, with an input of 80 mm to 100 mm per year accumulated over 10 years.

As far as drug molecules are concerned, the risks in wine production, with no contact between water and the harvest, are very low or non-existent. Monitoring of a few molecules in grapes and wine has not shown any contamination at the pilot sites studied in France.

The impact of reclaimed wastewater on soil microbial life is a major concern. Different papers suggested that in soils irrigated with RWW, the composition and assembly of the soil microbiota are altered mainly due to changes in the soil chemistry and plant physiology caused by the application of the RWW [24, 25].

Regarding the supply of fertilisers, Table 1 shows the nutrient input data based on RWW input at two experimental vineyard sites in the south of France. For nitrogen, there is a ratio of 1:10 between the two sites. Water from site one can provide up to 40 U/ha of nitrogen, while the quantities at site two are insignificant. Phosphorus inputs are negligible in both cases, which is satisfactory, as wine-growing soils are always sufficiently supplied with this element. As for potassium, the maximum of 30 U/ha applied corresponds to maintenance fertilisation [26]. These inputs are a positive aspect of wastewater reuse technology, but a few points must be borne in mind:

- The watering period at the end of the vine cycle does not coincide with the optimum time to apply nitrogen. It is essential to be vigilant about the risk of transfer during autumn rainfall, depending on the soil.
- For some very vigorous plots, an input of 40 U/ha may be excessive: how can the difference in needs between plots be managed?
- When it comes to potassium, be careful about the risk of an imbalance in the K/Mg ratio.

Table 1. *Nutrient input data, based on reclaimed wastewater input at two experimental vineyard sites in the south of France* [26]

Annual quantity of water per ha		Macronutrients provided (kg/ha) and percentages in relation to annual requirements					
		Site 1			Site 2		
(m³)	(mm)	N	P	K	N	P	K
300	30	13	0.3	9	0.7	0.04	8
500	50	21	0.6	15	1.1	0.07	14
750	75	32	0.9	23	1.7	0.11	21
1000	100	42	1.1	30	2.2	0.14	28

To conclude, the deployment of reclaimed wastewater (RWW) to date depends on changes in regulations and the increase in demand for agricultural water in relation to other uses. The high cost of investing in additional treatments for a limited period of use (two months in the case of winegrowing) means that a multi-use project approach associated with other needs (urban cleaning, fire protection, green spaces, different crops, etc.) should be encouraged. Any new project should consider a life cycle analysis compared to a more conventional water supply. In some cases, reuse may not be as good an idea as it seems.

IRRIGATION WATER QUALITY

In irrigation, the chemical quality of the water can affect plant health, longevity and the efficiency of the system in place, especially for subsurface irrigation. For fertigation, each use must be preceded by wetting the pipes and rinsing with clear water for one or two hours to avoid the buildup of deposits that could lead to clogging. In winter, all pipes must be drained entirely to prevent the risk of freezing or algae growth. The use of contaminated irrigation water negatively impacted some agricultural farms in the Ayaş District in the Central Anatolia Region, Turkey, revealing 63–91% distribution uniformity (DU), indicating a possible emitter clogging, leading to low uniform emitter discharge. This, in turn, led to high pressure requirements and a subsequently high cost of irrigation [27]. Managing the risk, particularly of clogging, helps to limit system maintenance costs.

Moreover, using low-quality water, such as wastewater recovered and reused for irrigation, may result in various problems, such as crop toxicity, damage to soil quality, diffusion of parasites and disadvantages in irrigation systems. Consequently, there are different water quality classifications to evaluate water quality and its usability for irrigation purposes. The most-used is the FAO (Food and Agriculture Organization of the United Nations) classification [28], in which problems concerning water quality in irrigated agriculture are subdivided into four groups related to:

- Salinity: salts in soil or water reduce the water availability to the crop to such an extent that yield is affected.
- Water infiltration rate: relatively high sodium or low calcium content of soil or water reduces the rate at which irrigation water enters soil to such an extent that sufficient water cannot be infiltrated to supply the crop adequately from one irrigation to the next.
- Specific ion toxicity: certain ions (e.g., sodium, chloride or boron) from soil or water may accumulate in a sensitive crop to concentrations high enough to cause crop damage and reduce yields.
- Miscellaneous: excessive nutrients reduce yield or quality, unsightly deposits on fruit or foliage reduce marketability and excessive equipment corrosion increases maintenance and repairs.

Under the ACCBAT project, an easily usable irrigation water quality tool (IWQT) was developed for farmers in Jordan, Tunisia and Lebanon to maximise the use of treated wastewater and desalinated brackish waters for irrigation purposes. The most significant and cheapest parameters of irrigation water quality were identified and clustered in three quality classes according to their effects on i) crop yield and soil fertility (agronomic quality indicators), ii) human health (hygiene and health quality indicators, iii) irrigation systems (management quality indicators). The list of IWQT parameters and their quality thresholds are shown in Table 2.

Table 2. *List of parameters used in the irrigation water quality tool (IWQT) and their quality thresholds* [29]

Parameters	Unit measure	Adequate for irrigation	Warning	Extreme Restrictions
pH		6.00 – 8.00	5.00 – 5.99	<5.00
			8.01 – 9.00	>9.00
EC	dS m^{-1}	<0.70	0.70 – 6.50	>6.50
SAR		<3.00	3.00 – 9.00	>9.00
E. Coli	Mean number per 100 mL	<1000		>1000
Intestinal nematodes	Arithmetic mean n. of eggs L^{-1}	<1		>1
TSS	mg L^{-1}	<200	200 - 400	>400
HCO3	mg L^{-1}	<150	150 – 300	>300
Fe	mg L^{-1}	<0.50	0.50 – 1.50	>1.50
Mn	mg L^{-1}	<0.10	0.10 – 1.50	>1.50
H2S	mg L^{-1}	<0.50	0.50 – 2.00	>2.00

The IWQT provides a series of recommendations created to guide farmers on the use of low-quality irrigation water classified in the WARNING quality thresholds.

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SUBTOPIC 4:
ADAPTATION OF FOOD CHAIN PROCESSES TO CLIMATE CHANGE AND DIVERSIFICATION

Climate change poses significant global challenges, impacting food supply chains in areas including agricultural output, income, prices, access, quality and safety. Temperature fluctuations and more frequent extreme weather events, such as heat waves, floods and droughts, affect fruit yields, quality and seasonality[1]. All food supply chain aspects — production, processing, transport, wholesale, retail, and consumption — can be influenced by environmental changes and disruptions [2]. Rising temperatures, prolonged droughts and shifting precipitation patterns are impacting fruit yields, quality and seasonality, especially in the Mediterranean area. Concurrently, consumer preferences are evolving towards more diverse, locally sourced and sustainably produced foods, necessitating a transformation across the fruit value chain. Strategies to enhance food supply chain resilience to climate change include: **post-harvest adaptation**, particularly in storage and packaging; fruit processing adaptation, especially in wine production; **optimising processes for energy savings; building energy-efficient facilities;** and **using IT production tools, flexible logistics and local sourcing**.

PROCESSING INNOVATIONS

Post-harvest adaptation through innovative packaging technology

The EU generates around 59 million tonnes of food waste annually [3], mainly from fruits and vegetables, which contribute to about 16% of greenhouse gas (GHG) emissions. Reducing waste saves resources in food production, and by 2030, the EU aims to halve global food waste at retail and consumer levels, reducing losses in food production and supply chains. As one way to do this, various post-harvest practices have been developed to extend the shelf life and quality of perishable fruits. The rising demand for organic and pesticide-free products is spurring interest in modified atmosphere treatments and low-oxygen packaging that influence the metabolic activity of fruit tissue and pathogens. Consequently, the market requires continuous innovation in packaging, leading to a growing demand for new technological solutions [4]. Within the framework of the Italian OG OLTREBIO, Ninetek Ltd and the University of Basilicata developed and patented BlowDevice®, an innovative device that enables bidirectional gas exchange across a sealed package to give it a breathable effect. This device is used to manage the atmosphere in the package headspace of fruits and vegetables packed in a modified atmosphere. A high level of carbon dioxide or a low level of oxygen controls the gas exchange for products with different respiration rates, avoiding fog formation on the internal surface of the package (Fig. 1) [5].

Fig. 1. Organic table grapes stored under MAP: (A) in breathable packaging equipped with BlowDevice® and (B) without BlowDevice®, showing fog formation [6]

The device was designed in several versions using biodegradable and sustainable materials, including Mater-Bi and polylactic acid (PLA). Moreover, the European Commission recognised the BlowDevice® micro-technology in biodegradable films as a 'key technology' in Europe on the Innovation Portal [7]. The device was combined with modified atmosphere packaging (MAP) to extend the shelf life (SL) of organic table grapes (cv. Superior and Scarlotta Seedless) and organic sweet cherries (cv. Lapins and Sweet Heart), mainly, in cold storage (CS). BlowDevice® preserved the quality of organic table grapes for over 45 days, reducing decay incidence by over 98% compared to samples packed without BlowDevice®.

Fig. 2. Bunches of Superior Seedless grapes on day 15, packaged with BlowDevice® (above) and with a micro hole (below) [8]

Furthermore, to simulate product storage conditions at the company level, an experiment was conducted on organic table grapes and organic sweet cherries by packing the fresh products into 5–6-kg bags with BlowDevice® and storing them in CS. After 15 days of CS, the products stored in bags were repacked into small boxes of approximately 300 g with BlowDevice® under MAP to simulate distribution and the retail market. The package with BlowDevice® enables a 62% reduction in decay in organic table grapes cv. Arra30 after 56 days in CS, compared to samples in open boxes, and 50% in organic sweet cherries cv. Sweetheart after 62 days, compared to samples in sealed containers (data not yet published). In recent trials, BlowDevice® in combination with MAP was also tested with organic strawberries (cv. Melissa), increasing the SL up to nine days [9], and with figs (cv. Dottato), maintaining high quality standards for up to 21 days at 2°C [10]. Breathable packaging with BlowDevice® technology represents a profitable and sustainable solution to prevent post-harvest decay of perishable fresh products, reduce food losses and enhance wider marketability.

Food processing adaptations

This section discusses strategies for adapting food processes to climate change, including optimising techniques for altered raw material characteristics and ensuring market-compliant production. Enhancing sustainability and flexibility contributes to product quality and long-term viability in a changing climate.

Wine: acidification and dealcoholisation methods

In recent years, climate change and rising temperatures have significantly impacted the grape and wine industry. Harvest dates are now earlier, caused by faster berry maturation, which results in (i) higher sugar levels, (ii) increased microbial proliferation, (iii) higher alcohol content, (iv) reduced acidity and higher pH, (v) imbalanced sensory properties and (vi) greater safety concerns (e.g., mycotoxin) [11,12].

These changes threaten wine typicity and sustainability. Current winery measures include acidification and dealcoholisation.

Wine acidification

A wine's acidity plays a key role in its organoleptic balance, contributing to freshness, tartness and crispness. A decrease in total acidity alters the colour and increases microbial instability. Acidity influences fermentation control, aroma preservation and SO_2 effectiveness, which diminishes as pH rises. Various acidification methods can be applied within regulatory limits: the increase must not exceed 53.3 meq/L (4 g/L tartaric acid) for must and wine (Regulation (EU) No 1308/2013, as amended by Regulation (EU) 2021/2117).

There are currently methods for chemical, physical and microbiological acidification:

Chemical acidification

According to the International Organisation of Vine and Wine (OIV) definition, chemical acidification means increasing the titration acidity by adding organic acids (only lactic acids, malic acid, tartaric acid, citric acids and fumaric acids can be used), as permitted, for wine and must acidification. Acidification is most commonly carried out by adding tartaric acid throughout vinification (i.e., pre-, mid- and post-fermentation). Different musts or wines may differ significantly in terms of ionic strength and buffering capabilities; in addition, there are different variations in pH and total acidity for the same treatments. Thus, the amount of acid to be added is determined based on the pH and total acidity for each individual case.

- **Tartaric acid:** Acidification with tartaric acid has been known for a long time, but has certain limitations, such as difficulty in accurately predicting the level of acidification.

- **Malic and lactic acids:** Acidification with organic acid occurs at the end of malolactic fermentation, except for the addition of malic acid, which takes place at the end of alcoholic fermentation.

- **Fumaric acid:** Authorised for wine acidification by the OIV in 2024.

Physical acidification

The two physical acidification techniques are electrodialysis and cation exchange resins, which are used commonly. In electrodialysis, the system uses a bipolar membrane and a cationic membrane configuration, allowing the selective extraction of cations. This method preferentially reduces the potassium cation content without affecting other elements or requiring the addition of chemicals to musts or wines. In comparison, acidification using ion exchange resins involves treating only a portion of the wine, which is highly acidified before being blended back into the original wine.

Building on these physical methods, the French Institute of Vine and Wine (IFV) has investigated various acidification strategies in the winery as critical methods of adapting winemaking practices to climate change. Among the authorised acidification techniques, physical methods stand out for their precision, enabling controlled pH adjustments even at high acidification levels. They also benefit from high automation, allowing 24-hour operation, although the associated investment costs can be significant. Ion exchange resins offer the advantage of a high treatment rate with a lower overall investment, since only a fraction of the tank needs to be treated. While tartaric acid remains the most effective organic acid for acidification, its use presents challenges in predicting final acidity levels. Malic acid is suitable only for red wines prior to malolactic fermentation, preserving microbiological stability, whereas lactic acid, although the least expensive, is rarely employed in practice and is considered a 'softer' acid better suited to red wine profiles [13].

Microbial acidification

Non-*Saccharomyces* yeasts and malolactic bacteria are key microorganisms for biological acidification in oenology. A comprehensive study reviews species/strains with potential for biological acidification of must and wine [14]. Traditionally, non-*Saccharomyces* wild yeasts in fermentations were linked to high acetic acid and off-flavours. However, researchers and winemakers now recognise their positive impact on the complexity of wine quality [15].

Yeasts of the *Lachancea thermotolerans* type can transform fermentable sugar (glucose and fructose) into lactic acid to the detriment of ethanol production. These yeasts lead to a drop in ethanol production (max. 1% vol.) and acidification by lactic acid. In general, *Lachancea* is used for 2 or 3 days, after which a classic *Saccharomyces* is used. If the *Lachancea* is left for too long, very high levels of lactic acid are produced (10 to 15 g/L), which has too great an impact on the organoleptic characteristics of the wines.

Dealcoholisation of wine

Dealcoholisation techniques are valuable for adapting wine processes to reduce alcohol levels, which increase with rising temperatures. Besides the sensory benefits of reducing heat and imbalance from high alcohol content, dealcoholisation meets the consumer demand for low-alcohol products. It also alleviates financial difficulties by making it possible to avoid certain taxes on alcoholic beverages that depend on alcohol content.

Various techniques can be considered for controlling fermentation to limit alcohol production. The IFV has carried out trials on yeast selection and the alcohol evaporation process.

- **Yeast selection:** Alcohol levels in wine can be influenced by yeast selection, which affects alcohol yield and sugar metabolism into by-products such as lactic acid and glycerol. Most non-*Saccharomyces* yeasts cannot ferment all sugars, so IFV trials have implemented sequential inoculation strategies. The most promising strains, combined with vineyard management practices, resulted in greater alcohol reduction. However, in red wines, high lactic acid production sometimes harmed sensory quality. This approach shows potential, but overall alcohol reduction was not systematic and remained below 2% v/v.
- **Evaporation of alcohol:** Wine can be partially dealcoholised through simple ventilation at ambient temperature and pressure. A 2% v/v reduction can be achieved in 8 hours with suitable equipment. Maximum efficiency occurs at around 80% humidity, which limits water loss. The process cools the wine, and its effectiveness improves with a larger air–wine contact surface. There is no significant impact on the wine's classic analytical characteristics, except for CO_2 loss. Currently being studied in small volumes, caution is needed due to oxidation risks. In larger volumes, the effect may be less intense because the wine surface area to vat volume ratio is less favourable for alcohol loss.
- **Stripping alcohol by fermentative CO_2 (not currently authorised):** Fermentative CO_2 is captured, compressed and reinjected at the bottom of the vat. This significant release of CO_2 carries alcohol, which is then condensed by a compressor and either reinjected into the vat or stored under pressure for later use.
- **Partial vacuum evaporation in alcoholic fermentation:** The alcohol is extracted through partial vacuum evaporation during alcoholic fermentation. This method preserves the aromatic compounds of future wines. In fact, when alcoholic fermentation continues after the alcohol has been removed, the yeasts produce new aromatic compounds, which is not the case when this method is applied to finished wine. This approach is currently being studied by the OIV for use during alcoholic fermentation and is authorised for finished wine.

Various processes can also be used to reduce the alcoholic strength of finished wine:

- **Distillation:** Despite high aromatic loss risk, distillation can be combined with reverse osmosis or nanofiltration to separate water, alcohol and small compounds such as organic acids and potassium. The distillation process yields concentrated alcohol (85–95% v/v) and can be directly recycled by the distillery.

Note: Only an authorised operator can perform distillation.

- **Membrane dealcoholisation:** Memstar's patented alcohol adjustment (AA) process involves two successive membrane operations. In the first stage, nanofiltration extracts a permeate primarily composed of water and alcohol. A membrane contactor consisting of hydrophobic membranes selectively extracts the alcohol from the water in the nanofiltration permeate. The dealcoholised permeate is then continuously reinjected into the treated wine, avoiding any concentration in the wine. The effluent produced is rich in alcohol, reaching up to 10% v/v, and accounts for 10–15% of the volume of wine treated for each degree removed. This effluent is considered a waste product.
- **Partial vacuum evaporation — spinning cone column (SCC) example:** This technology adjusts alcohol levels while preserving aroma, enabling the production of low alcohol wines (0.5% v/v). It removes 60–80% of alcohol, minimising water loss. The process involves two passes through a rotating column: the first extracts volatile compounds (aromas) at 30°C from a fraction of the wine; the second removes alcohol from the dealcoholised fraction. The aromatic extract is reintroduced, and this fraction is added back to the wine for dealcoholisation. This process is very interesting and preserves the organoleptic qualities of the wine. However, when used for heavy dealcoholisation (< 5% alcohol by wine volume), it can result in significant changes to the structure and balance of the wine.

Dealcoholisation techniques respond to the evolving climate as well as the diversification of the sector needed to maintain market share and cultivation areas. Interventions range from vine to wine, with various methods of partial dealcoholisation under study. However, complete dealcoholisation still raises numerous technical and legislative questions.

Optimising processes for energy savings

With climate change threatening the environmental and economic sustainability of Mediterranean perennial crops, optimising energy use in the food chain has become a strategic priority. In the wine and olive oil sectors, energy-intensive processes such as fermentation, temperature control and water management present significant opportunities for improvement. This section focuses on innovations that reduce the energy footprint of food processing, including energy-efficient winery design, the reuse of by-products such as fermentation CO_2 and olive pomace and winery waste. It also emphasises the use of monitoring tools to identify hotspots and optimise processes. These strategies minimise environmental impacts while enhancing resilience and competitiveness against climate and market fluctuations.

Monitoring tools — example in oenology

Precision oenology tools enhance energy efficiency in winemaking, where 90% of energy comes from fossil electricity and 10% from thermal processes such as water heating [16]. By integrating advanced technologies, data analytics and scientific control, winemakers can optimise temperature, humidity and fermentation across all production stages. This digital approach improves wine quality, resource efficiency and reduces greenhouse gas emissions.

SOLUTION AVAILABLE ON THE MARKET1

Onafis, a French wine tech company, has created a sensor and IoT system to monitor temperature, humidity and critical parameters in winemaking. Onafis installed 12 Atmos sensors and clamp meters in a Bordeaux winery to track wine ageing and energy consumption. By optimising conditions and cooling management (Fig. 3), the system saved €6,000 annually (30% of annual expenses) and reduced CO_2 by 10 tonnes. This case shows how precision oenology, through tools like Onafis', can develop traditional methods into energy-saving practices while maximising production conditions.

1. Onafis is one of the winning technologies/products from the Crowd-Writing Contest organised by CLIMED-FRUIT in 2023, aimed at private companies, to make mainstream farmers aware of the most recent innovations that promote resilience to climate change. See all winning technologies here.

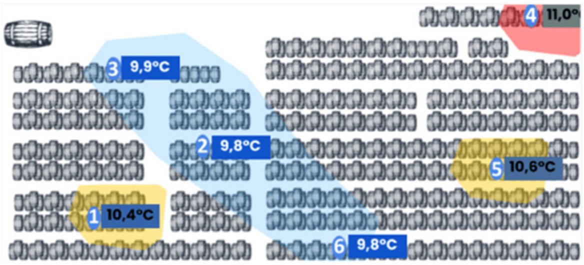

Fig. 3. Using cellar mapping to identify micro-climates to optimise evaporation loss and save on energy use [17]

Reusing by-products and co-products

Olive processing waste: biofuel example

Mediterranean countries produce 95% of the global olive oil supply [18]. The olive oil industry in the Mediterranean area is evolving due to climate change and environmental pressures. Olive oil production generates considerable waste, particularly olive pits and pomace, which pose disposal challenges but also present significant opportunities for energy recovery potential. Olive pits and pomace, with calorific values of 17–20 MJ/kg and 19–24 MJ/kg, can be used in biomass boilers or transformed into high-efficiency pellets, offering a renewable alternative to fossil fuels and reducing energy costs in olive mills [19, 20]. Olive pomace can be converted into fuel briquettes and pellets through drying, sieving, grinding and compression, providing biofuels for use during olive oil production, such as heating water during grinding, and enhancing circular, energy-resilient processing systems [21].

The EU BIOMASUD Plus project aimed to promote the sustainable market for Mediterranean solid biofuels used in residential heating, with the primary objective of developing integrated solutions to enhance the quality and sustainability of Mediterranean solid biofuels. This included extending Biomasud® certification to new biofuels and countries. The BIOMASUD Plus project has commercialised olive stone and cake as biofuels in Spain, Greece, Italy and Turkey, with olive cake being the second most used biofuel in Spain's industry in 2015. Unlike solid biofuels such as firewood and briquettes, the quality of olive stone is not graded by the ISO 17225:2014 standard. Spain has established a national standard (UNE 164003:2014) for grading olive pit quality for combustion purposes. Additionally, seven Spanish and five Italian olive stone producers are certified by the Biomasud quality system for Mediterranean biofuels. Innovative thermochemical (e.g., pyrolysis, gasification) and biochemical (e.g., bioethanol, biogas) conversions of olive by-products are being explored, though largely at the research stage.

Examples in the wine industry: recycling winery waste and fermentative CO_2

The LIFE ZEOWINE project is the first example of how winery waste can be reused efficiently. This project defined a method for producing ZEOWINE, a compost made from wine sector waste and zeolite that can be applied in vineyards to protect the soil.

The compost was applied for more than three years in several Italian vineyards using pomace and stalks mixed with 0.2 mm to 2 mm zeolite. Soil in the experimental plots was assessed immediately after treatment and again after six and 18 months, with the following improvements observed: 30% increase in soil organic carbon, 50% increase in microbial functionality, 38% increase in soil biodiversity and 40% reduction in bioavailable copper. The project team also evaluated grape and wine quality, finding improved balance between sugar and anthocyanins, as well as higher alcohol content. Yields increased, and grapes were heavier. Additionally, the recycling process showed clear environmental benefits, such as reduced water consumption due to better soil water retention, improved waste management by recycling winery residues instead of landfill disposal, lower CO_2 and NO_2 emissions compared to conventional fertilisers and enhanced carbon sequestration.

Another applied example is the recycling of fermentative CO_2 during the must-to-wine stage. Some of the gas produced during fermentation can be recovered and converted into dry ice. This dry ice is used during the harvest and in the bottling or pumping of white and rosé wines to inert the wine. For a production of 50,000 hl of white and rosé wines, for instance, about 6 tonnes of CO_2 can be recovered per day of harvesting, resulting in a total of 240 tonnes of CO_2. Since CO_2 consumption is around one tonne per day for this type of production, this would enable self-sufficiency during this period [22]. Another way to recycle fermentative CO_2 is to inject it into rinsing water to acidify it. Lowering the pH can halve the rinsing time after descaling or disinfecting, thereby reducing water consumption.

Designing energy-efficient buildings and production tools

To address climate change, agricultural and processing infrastructures for Mediterranean perennial crops must evolve to improve energy efficiency, resilience and sustainability. Wineries, olive mills and packing facilities are significant energy consumers due to heating, cooling and ventilation needs. Incorporating energy efficiency from the design phase through smart architecture, passive climate control, renewable energy systems and optimised layouts is key to cutting energy consumption and operational costs, thereby lowering the environmental footprint of food processing.

Projects in the Mediterranean demonstrate successful energy-efficient design in processing facilities. For example, in some facilities, gravity-flow architecture minimises pumps by using natural slopes for grape and juice transfer. Others employ passive cooling techniques such as underground cellars, high thermal mass materials, natural ventilation and green roofs to stabilise temperatures and reduce the reliance on mechanical refrigeration. In 2021, the Perelada winery in Spain was recognised as the first European winery to earn LEED® (Leadership in Energy and Environmental Design) Gold certification for outstanding energy efficiency from construction through operation. Key features include geometric energy use, efficient water and electricity consumption, material choices, sustainable processes, thermal insulation and natural light prevalence. Evening lighting uses minimal artificial light managed by an advanced control system. In Greece and Italy, olive mills are increasingly built or retrofitted with insulation, efficient LED lighting and heat recovery systems that repurpose energy from extraction for water heating.

In addition to design and energy sources, production tools can also be adapted. A study by the OIV found that using well-chosen yeasts and well-reasoned fermentation protocols can lead to significant energy savings in white winemaking without compromising quality. Additionally, online tools such as the one developed by the IFV help producers optimise energy consumption by estimating refrigeration needs. This tool can size refrigeration installations or visualise peak cooling requirements during harvest [23].

Supply chain adaptations: Olive Supply Chain in Salento (Southern Italy) after the Introduction of *Xylella fastidiosa* subsp. *pauca* (XF)

In the Salento region of southern Italy, the olive agro-ecosystem has endured for over 4,000 years. It represents an invaluable local heritage for the landscape, featuring ancient orchards primarily composed of traditional varieties such as Ogliarola Salentina and Cellina di Nardò [24]. These orchards were typically managed under low-input systems suited to the region's dry Mediterranean climate. Soil management involved minimal disturbance, relying on native fertility, while irrigation was rarely used, except during extreme droughts. Pruning occurred every 4 or 6 (or more) years, performed periodically to preserve tree structure and promote accessibility, and olive harvesting was mainly conducted by manually picking from the ground or semi-mechanically from the tallest olive trees to optimise yield and oil quality.

The outbreak of XF in 2013 caused widespread devastation, particularly affecting the region's predominant olive cultivars. This quarantine pathogen led to the rapid decline and death of trees, forcing the eradication of contaminated secular and old olive trees, resulting in 21 million trees disappearing, which disrupted traditional olive production systems. In response, the local olive supply chain underwent a major transformation, shifting towards the cultivation of resistant varieties such as Leccino and Favolosa (FS-17), which demonstrated tolerance to the pathogen [25]. With the introduction of young, resistant orchards, cultivation practices have evolved significantly. Soil management has become more proactive, incorporating organic matter and subsoiling to improve root development and tree vigour. Modern drip irrigation systems have been widely adopted to ensure consistent water availability, especially in increasingly frequent drought conditions driven by climate change. Pruning methods have also adapted; while ancient trees are maintained with minimal intervention, younger orchards are now pruned annually to regulate canopy structure, facilitate mechanisation and enhance disease control. The harvesting process has been modernised and fully mechanised, which is compatible with the uniform structure of the newer plantings. These adaptations reflect a broader systemic shift from traditional, extensive olive farming to a more intensive, resilient and technologically equipped model. While this evolution entails higher operational costs and landscape changes, it offers a viable pathway for sustaining olive oil production in Salento in the face of biological and environmental challenges. Many social actions have been taken in Salento to support agriculture and the farmers who want to restore the olive groves, such as OLIVAMI association.

Diversification and farm-scale adaptation strategies

Adapting food chain processes is essential to address the immediate impacts of climate change; however, true resilience requires a broader, systemic approach. Diversification and farm-scale adaptation strategies are key to building more robust agricultural systems capable of withstanding long-term climate variability. By integrating these strategies, producers can not only mitigate risks but also enhance the sustainability and economic viability of Mediterranean perennial crop systems.

Crop diversification for economic and environmental resilience

Crop diversification is essential for Mediterranean farmers, helping mitigate climate change impacts while improving soil health and economic resilience. Unlike monocultures, diversified systems reduce vulnerability to extreme weather and market fluctuations by spreading risk among species and varieties [26, 27].

Diversification can include intra-species strategies, such as selecting drought or heat-tolerant varieties such as Koroneiki, Arbequina, Lechin de Sevilla and Picholine Marocaine olives. Early ripening cultivars help avoid stress from low soil moisture. Inter-species systems, with complementary crops such as almonds, figs and pomegranates, enhance resilience and optimise resource use [28]. These systems reduce chemical inputs through natural pest regulation and improved microclimates [29].

Intercropping medicinal and aromatic plants with perennial trees in the Mediterranean Basin can boost yield, control pests/pathogens and weeds and enhance soil health [30]. In southern Spain, intercropping olive groves with aromatic herbs such as lavender, thyme and rosemary has been successful, attracting pollinators and providing secondary income from essential oils and dried leaves [31].

Agroforestry and mixed farming, where trees such as carob or pistachio are interplanted with legumes or cereals, enhance nitrogen cycling and diversify income [32]. Temporal diversification, such as crop rotation and staggered harvests (e.g., early apricots, mid-season peaches, late pomegranates), supports soil health and year-round economic stability.

As global warming and economic crises threaten Mediterranean horticultural and ornamental crop production, new challenges and opportunities arise. Pitaya, or dragon fruit, offers significant potential as a novel crop, requiring minimal water and thriving in high temperatures. With growing consumer demand for exotic fruits, pitaya is recognised globally as a superfruit [33].

Income diversification and market development

To enhance climate resilience, Mediterranean fruit growers can diversify income beyond agriculture. Agrotourism activities such as farm stays, guided harvests and tastings provide off-season revenue and promote local heritage [34]. Examples include vineyard tours and wine tastings in Tuscany, olive oil workshops in Andalusia, citrus walks in Sicily and almond blossom festivals in Mallorca. In the Istria and Dalmatia regions (Croatia), there is a focus on agrotourism with olive oil pressing, fig drying and local tastings. These activities connect visitors to traditional landscapes while supporting farm sales.

Producing value-added products from perennial crops boosts farm profitability and reduces dependency on volatile markets. Grapes can become wine, juice, raisins or grape seed oil, appealing to various consumer segments (Rossi et al., 2020). Olive growers can create extra virgin olive oil, flavoured oils, tapenades and cosmetics [35]. Citrus crops yield essential oils, marmalades, candied peels and dried slices for teas or cocktails, representing a valuable source of bioactive compounds for food, pharmaceutical and biomedical uses [36, 37]. Mediterranean nuts are turned into plant-based flours, drinks and high-protein snacks, meeting the demand for sustainable, health-focused foods.

Other income diversification strategies include agri-crafting workshops where visitors learn cheesemaking, bread baking or natural dyeing with farm plants, as well as wellness retreats. Yoga in vineyards, Mediterranean cooking classes or herbal walks can attract diverse tourists seeking authentic, nature-based experiences. Although these ventures require initial investment, they provide long-term stability and new marketing channels.

Circular economy principles can support sustainability. For example, winemaking grape pomace can be reused as compost, animal feed or natural dye [38; 39]; olive pits can be processed into biofuel or bioplastics; and citrus peels can be used in cleaning products or essential oils. These practices reduce waste, lower costs and create new revenue from agricultural by-products.

Collaborating with local tourism boards, sustainable travel agencies and cultural networks can increase visibility and customer reach. By merging value-added processing with agrotourism and circular practices, Mediterranean farmers can reduce climate risks, enhance income security and contribute to vibrant rural economies rooted in heritage and innovation.

Improving staff skills: example in a winery

The GreenVineyards project enhances the skills of wine sector workers to address climate change. Upskilling winery staff is essential for resilience and sustainability, creating a positive ecological footprint, preparing workers for green jobs and preventing skill shortages, which helps wineries remain competitive and responsible. The course, comprising 13 units, targets industry skill gaps to foster a sustainable wine sector, with the following focuses:

- Climate-resilient viticulture emphasises drought-resistant grape selection, optimised irrigation and soil management for productivity in changing climates.
- Sustainable winemaking trains staff in energy-efficient practices, organic farming and renewable energy to reduce carbon footprints.
- Technological advancements necessitate digital skills. Training in climate sensors, AI analytics and digital traceability helps wineries optimise management and supply chains.
- Learning about alternative grape varieties, sustainable packaging and eco-friendly distribution enhances staff capability to meet market and climate demands.
- Understanding climate policies and sustainability certifications aids compliance and competitiveness. Training in organic, biodynamic and carbon-neutral production, along with participation in carbon credit programs, strengthens climate action efforts.
- Investing in continuous learning boosts wineries' resilience and sustainability.

Skilled staff are essential for adapting to climate change and ensuring a prosperous future for the wine industry.

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SUBTOPIC 5:
PRESERVING BIODIVERSITY IN THE MEDITERRANEAN AREA FOR BETTER RESILIENCE TO CLIMATE CHANGE ISSUES

Biodiversity loss and climate change are two major environmental challenges, with intensive agriculture significantly impacting ecosystem degradation. The widespread use of synthetic agrochemicals and the homogenisation of agricultural landscapes have contributed to the rapid decline of flora and fauna. According to the WWF's Living Planet Report 2022 [1], wildlife populations have declined by an average of 69% over the past 50 years. While land-use change remains a key factor, climate change will become the primary driver of biodiversity loss by mid-century [2]. Preserving Mediterranean biodiversity is vital for ecosystem resilience, sustainable agriculture, and food security. However, unsustainable agriculture leads to biodiversity loss. Initiatives like the EU Biodiversity Strategy 2030 (protecting 30% of land and sea), the FAO Action Plan 2024–2027 (sustainable land and water management) and national biodiversity strategies promote habitat restoration and sustainable resource use. Coordinating global, regional and local strategies is crucial to integrating biodiversity conservation into climate adaptation efforts, ensuring long-term ecosystem stability and agricultural sustainability.

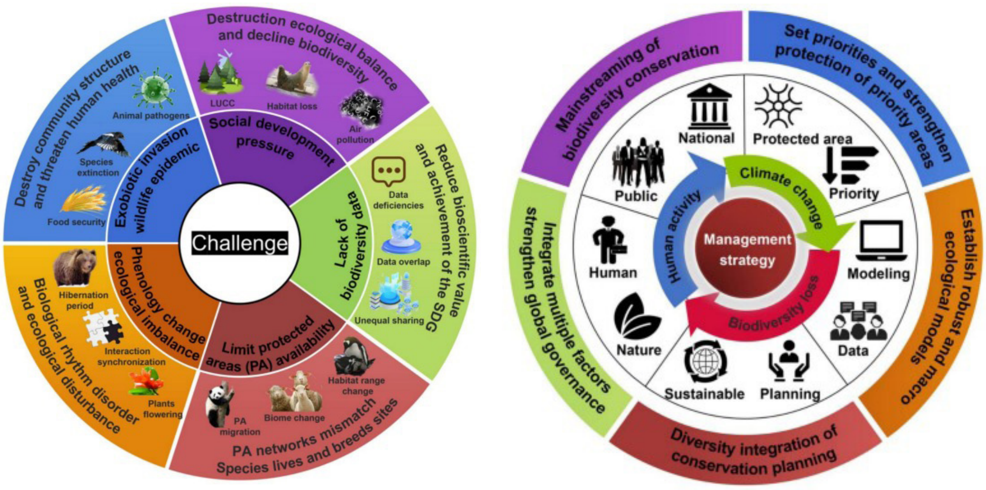

Fig. 1. Biodiversity conservation in the context of climate change: A) challenges B) management strategies [3]

Innovative agroecological practices in the Mediterranean region are being implemented to preserve biodiversity and address challenges (Fig. 1A). In the 2030 biodiversity framework, successful implementation will require integrated conservation planning among scientists and policymakers. The management strategies for biodiversity conservation in the context of climate change are illustrated in Fig. 1B.

This review presents a non-exhaustive list of examples of practices from the Climed-Fruit project and several other initiatives that help to preserve and enhance biodiversity in Mediterranean perennial crops at the crop, field, farm and landscape levels.

PRESERVING CROP DIVERSITY

Climate change is one of the key drivers of biodiversity loss and threatens the survival of the strategic reservoir of crop genetic resources needed to adapt production systems to future challenges. Modern agricultural systems, however, often rely on a narrow genetic base, increasing the risk of genetic erosion and reducing the sector's ability to respond to future challenges.

This section explores different strategies for conserving and utilising crop genetic resources, from safeguarding traditional varieties to breeding new cultivars. It highlights the importance of ex situ and in situ conservation, the rediscovery of old varieties and wild relatives and the development of new resistant cultivars, such as PIWI grape varieties, which aim to reduce chemical inputs while ensuring long-term sustainability.

Avoiding the risk of genetic erosion

Genetic diversity is essential for fostering resilient crops, particularly regarding climate change. Agrobiodiversity, which includes a variety of crop species and landraces, is a valuable source that provides a genetic pool for climate adaptation and disease resistance. Additionally, crop wild relatives and landraces offer a crucial yet underutilised source of genetic diversity for breeding heat- and drought-tolerant cultivars and improving resistance to diseases and pests.

Loss of genetic diversity for perennial crops in the Mediterranean region

In Mediterranean perennial crops such as olives, grapes and fruit trees, genetic diversity has historically allowed adaptation to a wide range of environmental conditions, pests and diseases. However, modern agricultural practices, driven by the demand for high yields and market uniformity, have significantly reduced the number of species and varieties cultivated. This trend increases the vulnerability of these systems to climate variability, emerging diseases and soil degradation, making it crucial to preserve and promote genetic diversity in perennial cropping systems. For example, concerning olives, although 139 varieties [4] have been identified across the Mediterranean (IOC, 2000) [5], only a few varieties were planted in modern orchards. In Spain (the largest olive-producing country), only three varieties (Picual, Arbequina and Hojiblanca) are planted in over 90% of the orchards and dominate production. The widespread use of super high-density olive plantations that require large inputs, such as irrigation water, and are based on a limited number of clones of a few varieties can also prove problematic under climate change conditions.

Main action for the recovery and conservation of perennial crop genetic resources in the Mediterranean region

Recovery and conservation of perennial crop genetic resources in Spain

The conservation of plant genetic resources has traditionally relied on ex situ methods, such as gene banks, where plants are preserved outside their natural habitats. Notable examples include the El Encín Vineyard Collection in Madrid (3,000 grapevine accessions) and the Alameda del Obispo Olive Germplasm Bank in Córdoba (more than 800 olive varieties). However, climate change has highlighted the need for a complementary approach integrating in situ conservation and preserving plants in their natural environments. This includes genetic reserves (monitoring wild populations) and on-farm conservation, where farmers manage the diversity of cultivated plants. National programs are increasingly adopting this approach to maintain crop adaptability.

Recovery and conservation of perennial crop genetic resources in France

In the case of vines, France has developed an extensive grapevine heritage, including ancient varieties, modern crosses and mutations. Collections have documented around 550 varieties [6], with 377 officially authorised for cultivation in the French official national vine variety catalogue. Conservation efforts, through conservatories subjected to agronomic assessments, play a crucial role in preventing genetic erosion. Each year, new varieties — whether traditional French and foreign grape varieties or modern breeding selections — are added to this list, enriching France's viticultural diversity.

Recovery and conservation of perennial crop genetic resources in Italy

The Mediterranean Germplasm Database (MGD) is the reference database for the agro-food plant germplasm collection stored at the Institute of Biosciences and Bioresources (IBBR) of the Italian National Research Council (CNR) in Bari, Italy. The collection contains about 220 accessions of citrus fruits of great agronomic, historical and ornamental value, over 200 accessions of both domestic and wild olive trees and about 480 accessions of grapevine. The varieties belong mainly to the Mediterranean agro-food systems, some of which have great economic importance. The main objective of the Perennial Plants Germplasm Repository (PPGR) collection is to safeguard the genetic resources of perennial plants that are of interest to Italian and Mediterranean agriculture.

In addition, the regional centre for the ex situ conservation of native fruit, vine and olive is located at the Basile Caramia Centre for Research, Experimentation and Training in Agriculture (CRSFA), located in Locorotondo (southern Italy). The germplasm conservation fields are situated in various locations to meet different species' soil and climatic requirements. The Locorotondo countryside hosts approximately 2,500 accessions belonging to 540 distinct grapevine cultivars (regional, national and international germplasm). The collection fields for viticultural germplasm will be expanded at the Ferragnano Operational Section in Locorotondo, and the existing collection will be augmented by incorporating new accessions. In Palagiano, a new conservation field for sanitary improved germplasm has been established in the area of Conca d'Oro, where there are also approximately 220 accessions from 62 different olive cultivars (regional and extra-regional germplasm). The site also contains 93 accessions of sweet orange, clementine, mandarin, lemon, lime and related hybrids and rootstocks. Moreover, the Locorotondo countryside is home to about 1,000 varieties of fruit species: 210 almond trees, 215 fig trees, 193 pear trees, 80 cherry trees, 70 peach trees, 64 apricot trees, 52 plum trees, 32 apple trees and 60 minor fruit trees.

EXPLORATION OF OLD OR WILD VARIETIES THAT COULD PROVE INTERESTING IN THE FACE OF CLIMATE CHANGE

In the Mediterranean, local crop varieties are being rediscovered for their resilience to extreme conditions and their contribution to dietary diversity [7, 8]. These varieties have adapted to resource-limited environments and may serve as alternatives to high-yield modern crops that have lost resistance to stress factors due to intensive breeding [9].

Continuing with the example of viticulture, wild resources of the subspecies *Vitis vinifera* ssp. *sylvestris* (wild grapevine) must be considered. These are critically endangered, with only a few hundred individuals recorded in France, for instance, often isolated or in small populations, lacking natural regeneration and facing annual declines. Some of these wild vines are preserved in the national public ampelographic collection (INRAE Domaine de Vassal, France) or regional conservatories (e.g., South-West France, Charentes). Numerous diversity characterisation studies are conducted by research partners. Some varieties may show traits better adapted to climate change (maturity period, acidity level, canopy architecture, etc.), and additional observations include aromatic precursor analysis, water stress assessments and research on disease resistance. For example, for over three years, the Valovitis project studied more than 60 forgotten grape varieties originating in the Pyrenees territories (southwest France and northern Spain). Their agronomical and oenological traits were referenced, and a catalogue has been produced. Similar work is being done in Spain (VITISAD Project) and Italy.

GENETIC DIVERSITY AS LEVERAGE AGAINST DISEASES

In the face of increasing disease pressures exacerbated by climate change, genetic diversity is fundamental in ensuring the resilience and sustainability of Mediterranean perennial crops. Farmers and researchers can mitigate the impact of major pathogens while maintaining productivity by leveraging diversity at different levels: rootstocks, cultivars and breeding programs. From selecting resistant rootstocks in olive and citrus to breeding disease-resistant vine varieties, biodiversity is key to reducing dependence on chemical inputs and enhancing long-term crop adaptation. This section explores various strategies with examples demonstrating how genetic diversity contributes to disease management in perennial systems, focusing on olive, citrus and viticulture case studies.

Creating new varieties: the example of PIWIs

Plant breeding is also a pillar that should be integrated into crop diversity. The development of vine varieties resistant to fungal diseases (PIWIs) has accelerated over the last 15 years. This is part of the wine industry's strategy to reduce the use of plant protection products, which is one of the industry's major challenges. Consumer acceptance and the quality of the wines produced from PIWI varieties are key issues in adopting these varieties, and these are some of the questions raised by the SUWIR project conducted in South Tyrol. The latest work in France has led to the creation of so-called ResDur varieties (from the French '*resistances durables*', i.e., 'long-lasting resistance'), which combine several resistance factors according to the principle of gene pyramiding. Three series of crosses have been carried out since the start of the programme. Four ResDur 1 varieties have been registered in the French official national vine variety catalogue and classified in 2018: Artaban N, Vidoc N, Floreal B and Voltis B. In 2022, five new varieties expanded the range of new varieties from the ResDur programme included in the official national catalogue: Coliris N, Lilaro N, Sirano N, Selenor B and Opalor B.

Selecting rootstock as a strategy against diseases

In olive cultivation, *Verticillium* wilt represents the most serious fungal disease, leading to high tree mortality and yield losses, particularly in Mediterranean regions. The susceptibility of olive trees to *V. dahliae* is influenced by the virulence of the pathogen and the genetic background of the host plant. Research in Spain has demonstrated that avoidant or resistant rootstocks are more effective than tolerant rootstocks in reducing the grafted plant's susceptibility to *V. dahliae* [10]. The cultivar 'Picual' grafted onto GUA3, AMK27 and especially the cultivar 'Frantoio', showed fewer symptoms and a delay in the development of the disease, exhibiting low relative area under the disease progress curve (RAUDPC), moderate symptoms with final mean severity (FMS) and a low percentage of dead plants (PDP) (Fig. 2).

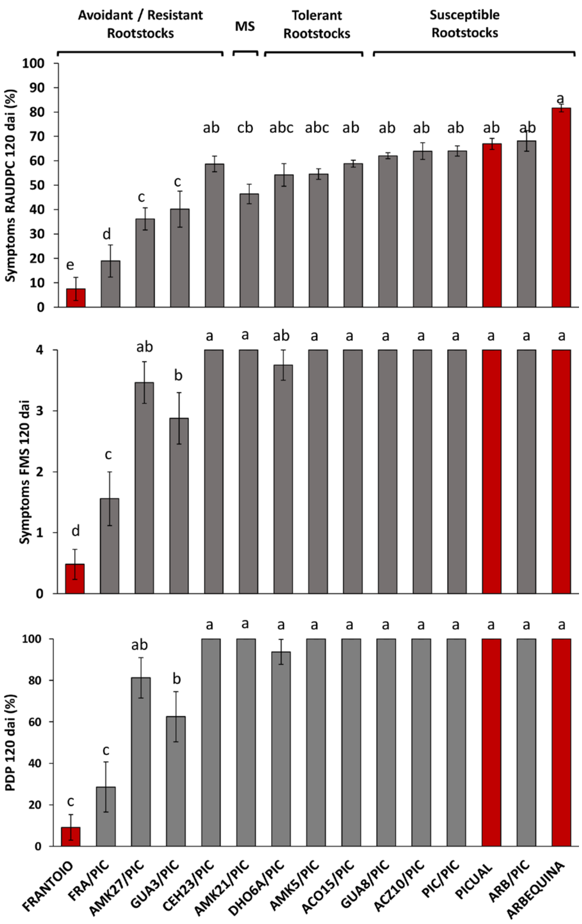

Fig. 2. RAUDPC (A), FMS (B) and PDP (C) of cultivar 'Picual' grafted onto different olive rootstocks inoculated with the Verticillium dahliae defoliating isolate VD117, at 120 days after inoculation (dai). Red bars correspond to non-grafted reference cultivars: the resistant 'Frantoio', the moderately susceptible 'Arbequina' and the extremely susceptible 'Picual,' according to the levels of resistance described by López-Escudero et al. (2007)

Citrus tristeza virus (CTV) has devastated citrus production in recent years, leading to the loss of nearly 100 million plants, including sweet oranges, mandarins and grapefruits, propagated on sour orange (*C. aurantium*), which is the historically dominant rootstock in the Mediterranean basin. Few genotypes have shown promise as CTV-tolerant rootstocks, combining high yield, fruit quality and resistance to abiotic (frost, salinity) and biotic (*Phytophthora* spp., the viroids of citrus exocortis and hop stunt) stressors. Among these, Volkamer lemon (*C. volkameriana*), Carrizo citrange (*C. sinensis* × *Poncirus trifoliata*) and Forner-Alcaide no. 5 (*C. reshni* × *P. trifoliata*) stand out as viable alternatives [11]. A new disease is currently causing severe damage to citrus crops in areas of Florida, Brazil and California: HLB, caused by the bacterium *Candidatus liberibacter*. This disease has no cure, and it is believed that its control will be based on the use of rootstocks that are resistant or tolerant to the growth of the bacterium. These rootstocks are currently being researched by universities around the world.

Selecting tolerant/resistant cultivars as a strategy against diseases

Xylella fastidiosa subsp. pauca (Xfp) is a bacterial pathogen that has caused significant economic and environmental losses in olive trees in southern Europe, particularly in Italy, where legislative measures (Commission Implementing Decision (EU) 2017/2352) have limited new plantations in infected areas to resistant varieties. In Salento (southern Italy), the resistance of the Leccino cultivar in the field was confirmed compared to Ogliarola salentina [12]. Additional resistance traits were identified in the patented cultivar FS17® (Favolosa®), characterised by low bacterial population size and limited desiccation [13]. A field study in Cassano delle Murge (Bari) evaluated these cultivars in a super high-density (SHD) system, revealing FS17®'s strong adaptability and high yield potential. In contrast, Leccino and other traditional cultivars were less suited to intensive production [14].

ENHANCING BIODIVERSITY AT THE PLOT AND FARM LEVELS

Numerous practices can be used to improve biodiversity within a plot and at the farm level. Encouraging the presence of green infrastructures is an initial method that has proved its worth, as they play a key role in soil health, biological pest control and pollination services. These infrastructures are often considered networks of multifunctional natural and semi-natural areas designed or preserved and managed to support ecosystem service delivery and biodiversity conservation.

The LIFE IGIC project has adopted this approach, implementing various forms of green infrastructure within olive groves. This has involved the creation of microhabitats such as stone refuges, brush piles and water ponds, which provide valuable nesting and shelter sites for fauna. The project also involves planting diverse species, including aromatic and medicinal plants, shrubs and trees that can be used as cover crops and hedgerows and to enhance biodiversity.

Many farming practices can be used to create additional green infrastructures or enhance existing ones. The following section describes some of the main ones.

Intercropping

Planting different crops together to enhance biodiversity, known as intercropping, is a specific form of multiple cropping where two or more crops are grown in the same field within a year to achieve more sustainable and profitable crop cultivation. Intercropping generates several benefits for the agricultural ecosystem, such as increased utilisation of natural resources such as water and nutrients, greater conservation of resources and the promotion of soil biodiversity [15]. Additional benefits include improved pest and disease management, higher populations of pollinators and natural enemies due to floral intercropping and enhanced yield stability compared to monocultures (Fig. 3).

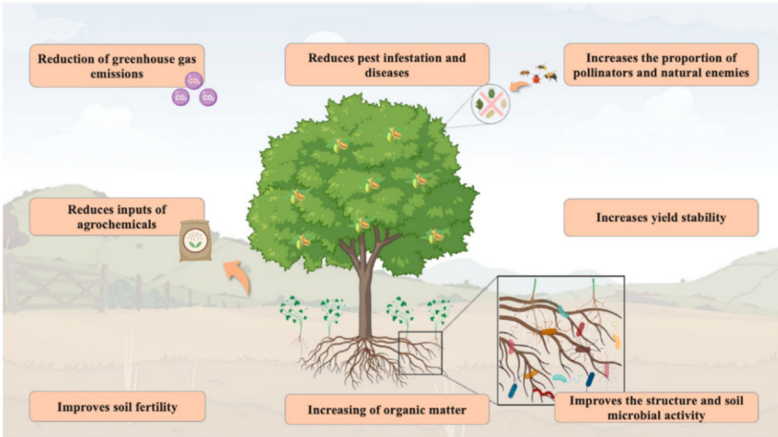

Fig. 3. Benefits generated by the interspecific relationship between crops in the intercropping system[16]

Interspersing cover crops, legumes or aromatic plants between the main crop rows enhances plant diversity, directly influencing overall ecosystem biodiversity. Additionally, the different plant heights, root systems and growth habits create microhabitats that support various organisms. Crop mixtures increase the population of different arthropods, insects and birds [17]. Intercropping aromatic and medicinal plants with nut trees in integrated management systems has been shown to have significant potential for increasing yields, controlling pests/pathogens and weeds and improving soil health and the quality of commercial crops [18]. The crop mixture can potentially attract beneficial insects, which have the potential to keep the harmful pest population below the threshold level.

Soil covers

Spontaneous covers: a natural ally for boosting biodiversity in perennial crops

Recent studies on biodiversity conducted in pear orchards and vineyards [19, 20] showed that spontaneous cover supports natural enemies and specifically increases the population of *Hymenoptera* (86%), minute pirate bugs (80%), spiders (40%), mites and thrips (100%). A similar study conducted in Spain by the OG CARBOCERT examined the use of permanent cover with spontaneous vegetation in alleys, rows and slopes of almond plantations. The findings revealed a significant increase in biodiversity, estimated at 76%, highlighting the ecological benefits of this approach.

Similar results can be observed in olive groves and other perennial crops [21]. It has been found that natural vegetation mowing, instead of tilling, increased biodiversity and can be an asset to favour the overall parasitism of the anthophagous generation of the olive moth *Prays oleae* [22]. It also boosted plant species richness and diversity, as well as grass and straw cover.

Cover crops: a key to boosting soil health and biodiversity

Cover crops are plants grown primarily to protect and improve soil health rather than for harvest (unlike intercropping, where all the crops are harvested). They are a sustainable solution to mitigate soil erosion, soil fertility reduction, water-holding capacity, biodiversity loss and other ecosystem alterations due to extreme climate events.

A study conducted by the Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB) [23] in rainfed vineyards located in the Douro Demarcated Region (north-eastern Portugal) evaluated the impact of soil cover management on soil functional biodiversity, vine performance and grape quality. Three different inter-row soil management practices (tillage, rolling and mowing) were applied (Fig. 5), and several parameters related to biodiversity were assessed (flora, soil-surface arthropods, decomposition of plant material in the soil and feeding activity of microfauna and mesofauna).

Fig. 4. Spontaneous dryland cover (left) and spontaneous plant cover maintained by mowing (right) (photos: IRTA)

Fig. 5. a) TILL– tilled soil, b) MOW – mowed vegetation, c) ROLL – rolled vegetation [23]

Results suggest that ground cover modalities (rolled and mowed) promoted more functional biodiversity. Cover crops increased epigeic arthropods by 344% compared to tillage. In the case of predators (*Aranea, Carabidae*), their numbers increased by 77%. The abundance and richness of soil-living arthropods, mainly represented by *Acari* and *Collembola*, were positively affected by cover crops, increasing, respectively, by about 100% and 77% (Fig. 6). The biological soil quality index (QBS-ar), obtained by using the data on soil-living arthropods, was also positively affected by ground cover (increasing by about 62%).

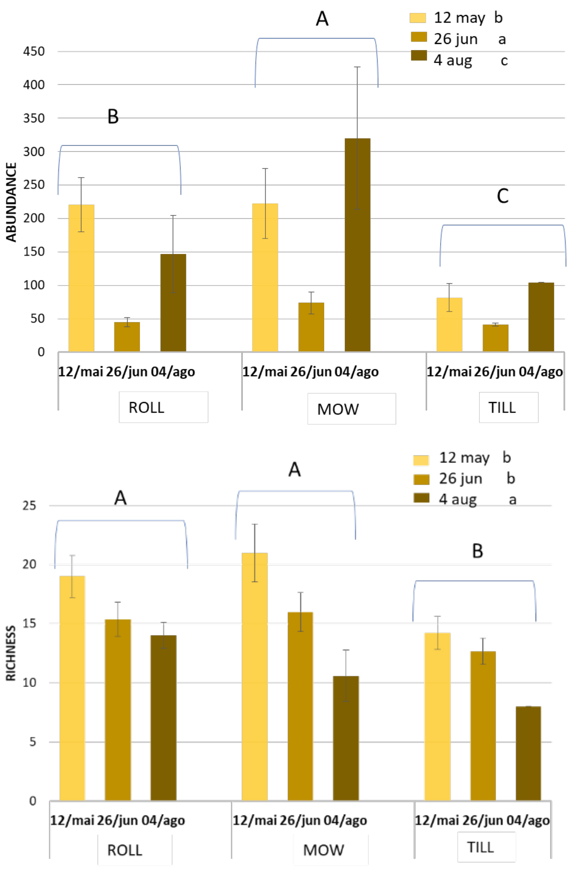

Fig. 6. Effect of different ground management on abundance and richness of arthropods [23]

Another study has been conducted in the framework of the GASCOGN'INNOV project in Gascony, southern France, evaluating the impact of different viticultural practices on soil biology across 23 test plots with varying soil types. The study focused on green manure, a cover crop rich in leguminous species that enhances soil fertility and structure by producing biomass that is returned to the soil. Results showed that green manure and reduced soil perturbation improved biodiversity by an estimated 29–45%, positively impacting earthworm abundance and activity, increasing microbial biomass and soil biological activity, and supporting arthropod and micro-arthropod populations through mulching without negatively affecting microbial biomass. Similar results were observed within the framework of the OG New Practices in Rainfed Olive Groves in Portugal, which assessed the impact of short-cycle and naturally reseeding leguminous cover crops on biodiversity, estimating a 45% improvement. Additionally, reducing tillage intensity and extending plant cover duration enhanced the abundance of earthworms, nematodes, bacteria, and fungi, although it did not necessarily increase their diversity [24, 25].

Mulching: recycling in favour of biodiversity

Mulching in perennial crops involves covering the soil surface with organic (e.g., straw, wood chips, compost) or inorganic (e.g., plastic films) materials to conserve moisture, suppress weeds, regulate soil temperature and improve soil health. It also enhances biodiversity by fostering soil microbial life and reducing erosion.

The OG GO CITRICS recycled rice straw as mulch for the citrus orchard row to adapt to extreme heat and drought conditions. Among many benefits, such as water saving, better control of weeds, lowering soil temperature and improving the structure and fertility of the soil, it also increases biodiversity related to the soil microorganisms and worms by 15% (estimated) (Fig. 7).

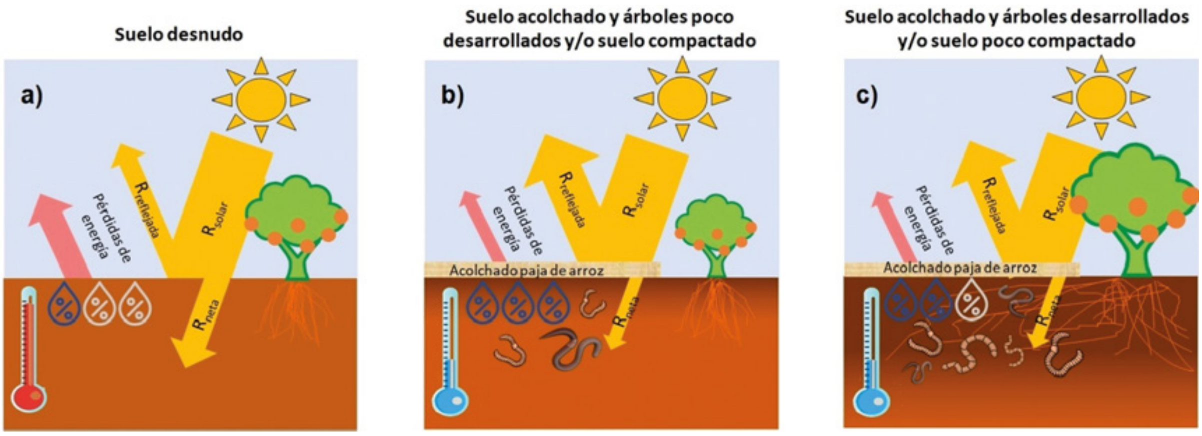

Fig. 7. Soil energy balance in the different treatments and plantations: a) bare soil, b) mulched soil and underdeveloped trees and/or compacted soil in Paiporta and c) mulched soil and developed trees and/or loosely compacted soil in Sueca [26]

The Vitimulch project also tested different types of mulch under vine rows in the south of France. Each type of mulch, resulting from a circular economy approach, was installed to a height of around 15–20 cm and a width of 60 cm. The application of mulches positively affected earthworm count compared to chemically weeded rows (for more information, please see Subtopic 1).

Agroforestry systems, buffer strips and hedgerows

Agroforestry, which consists of growing woody vegetation (trees or shrubs) with plant and/or animal production systems, has become a practice used by farmers around the world due to the constant availability of food, fruit, timber, fodder and fuelwood, which has created sustainability in their livelihoods.

In the short and medium term, introducing trees into the agroecosystem brings landscape diversity and variability of vegetation strata and, therefore, new ecological niches. The tree and all its components (branches, leaves, flowers, fruit, cracks in the trunk, roots) provide a 'mix' of habitats, refuges, food resources and hunting, breeding and wintering areas. In theory, trees help to maintain a wide variety of species (insects, spiders, small mammals, birds, reptiles, etc.). Over the long term, the development of trees leads to the presence of a high tree layer within the plots and the appearance of cavities and cracks, all of which are microhabitats favourable to certain species (bats, nesting birds, etc.).

Impact on aerial biodiversity

Introducing trees in agricultural systems can provide additional resources and refuges for beneficial organisms such as predatory mites, arachnids, lacewings and parasitoids, as seen in viticulture (e.g., the PIRAT project in France). However, the Vitiforest project in young vineyard plots (eight years old) in southern France did not find a significant impact from trees on pests or beneficial species. The complex interactions within food webs, influenced by factors such as species, climate and vine physiology, make it difficult to generalize results. Therefore, integrating trees should be part of a broader ecological approach, including managing field edges through late mowing, planting hedges and reducing phytosanitary inputs.

Impact on earthworms

Earthworms are both indicators of and players in soil quality. They reveal the state and uses of the soil because they are intimately linked to its constituents and react to changes. Earthworms are sensitive to many aspects of modern agriculture: phytosanitary inputs, soil compaction and tillage that destroys galleries and buries organic matter and groups of earthworms living on the surface. On the other hand, any action that increases the amount of organic matter in the soil is positive for earthworms.

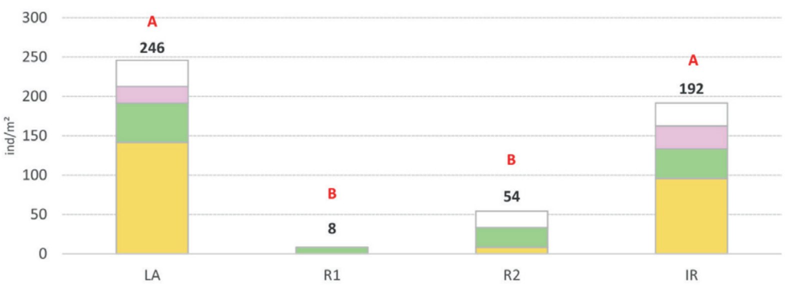

Fig. 8. Counting earthworms in an agroforestry French vineyard (six rows of vines framed by two rows of trees, planted 3.25 m from the first row of vines, with the trees spaced 10 m apart)

Total mean of black-headed anecic/m² (yellow), of endogeic/m² (purple), of red-headed anecic/m² (green) and of undetermined (white), on the tree line (LA), under the row of vine at 6 m from the tree line (R1), under the row of vine at 8.25 m from the tree line (R2), in the interrow (IR)

The trials conducted in France in viticulture, within the Vitiforest project, demonstrated that the presence of trees had a significant impact on the distribution of earthworms (Fig. 8). Except for one plot, more anecic and endogeic earthworms were found in the tree line. A gradient of decreasing frequency was then noted as one moved away from the tree line. It was also noted that worked areas (inter-row or vine rows) had a significantly lower number of individuals than areas with permanent grass cover.

Impact on soil microbiology

The presence of trees in agricultural plots can enhance microbial diversity by introducing environmental heterogeneity (plant cover and microclimate), creating ecological niches, providing nutrients through the rhizosphere and litter and reducing soil contamination from phytosanitary treatments. A study under the Vitiforest project in a 7–8-year-old agroforestry vineyard found good overall microbiological quality but no significant impact on microbial abundance and diversity at varying distances from trees, likely due to their young age and limited root development. However, trees influenced the composition of microbial communities, favouring taxa associated with organic matter decomposition and stimulating mycorrhizal fungi growth.

ENCOURAGE THE PRESENCE OF POLLINATORS

Preserving pollinator and predator biodiversity enhances ecosystem resilience and agricultural productivity by supporting essential ecological functions. Key strategies include planting diverse flowering species, conserving wild areas, reducing pesticide use and adopting integrated pest management (IPM) and organic farming. Crop rotation, cover crops and providing nesting sites for pollinators and birds further support biodiversity and natural pest control, as well as reduce yield losses [27, 28] (Letourneau et al., 2009; Dainese et al., 2019). Orchards, due to their perennial structure, attract both pollinators and natural enemies of pests [29]. The revised EU Pollinators Initiative for 2030 prioritises species conservation, habitat restoration, reducing pesticide impacts, enhancing urban pollinator habitats and addressing climate change to counter pollinator decline.

Pollinator habitat restoration and enhancement

Enhancing pollinator biodiversity through pollinator-friendly practices (Fig. 9) in orchards is key, as insect pollination boosts fruit production. The best approach is often to let nature take its course, with forests serving as pollinator refuges. In intensive cropping, agroecological infrastructures — wildflower strips, hedges, legume-rich areas and buffer zones — support pollinators. Flower strips in rotations enhance pollinator diversity, benefiting common and rare species. Hedges provide food, nesting sites and habitat connectivity, while flower-rich hedgerows extend the flowering period. Grassland leys, legume-rich fallows and cover crops in orchards offer food in autumn and early spring. In vineyards, pollinators aid ecosystem services and cover crops boost biodiversity. Wild bees, often more effective than honeybees, need nesting sites such as bee hotels or undisturbed soil. Resources from groups like the Xerces Society guide habitat creation.

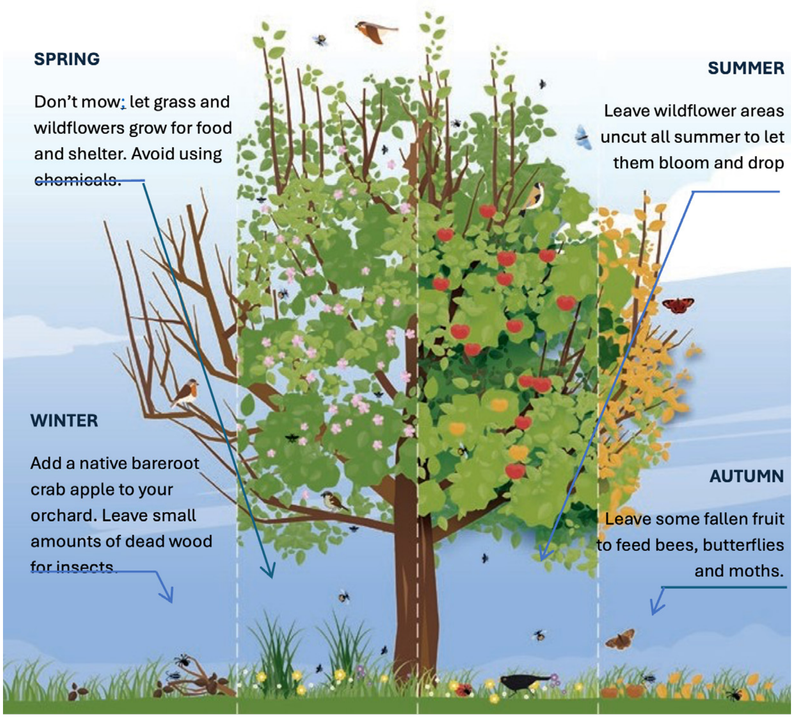

Fig. 9. Pollinator-friendly practices in the orchard
Source: All-Ireland Pollinator Plan, https://pollinators.ie/orchards-for-pollinators-a-new-free-flyer/

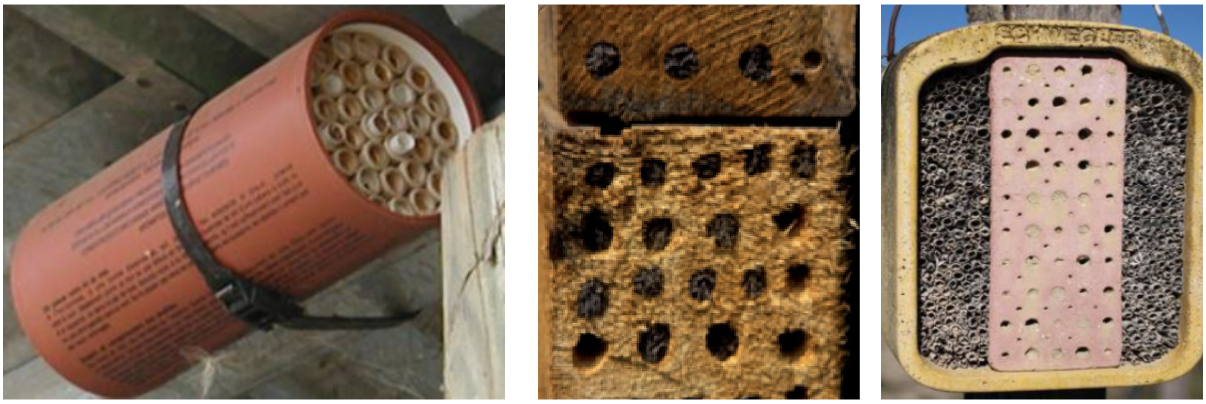

Fig. 10. Nesting habitats for cavity-nesting solitary bees (from left to right: hollow stem bundle, holes drilled in wood, commercial bee box mixing hollow stems and cavities in clay)

The BIOFRUITNET project, focused on organic pome, stone and citrus fruits, provides recommendations regarding suitable flowering trees, shrubs and bulbs, as well as on the number, placement and dimensions of nest boxes and cocoons for wild bees, in particular for mason bees such as the European orchard bee (*Osmia cornuta*) and the red mason bee (*Osmia bicornis*). Both mason bees fly within a perimeter of 50–200 metres, so the number and placement of the nesting boxes (Fig. 11) should be adapted accordingly. Around 2000 cocoons (2–3 nesting boxes) are needed to pollinate a 1-hectare low-stem fruit orchard.

Fig. 11. Nesting box for mason bees (left); mason bees need holes for nesting (right)

A study in two cherry orchards in Sefrou, Morocco [30] examined the attractiveness of bee hotels to wild bees. Two types of bee hotels (Fig. 12) — a wooden log nest and two small wooden tray nests — were installed at each site, 30 metres apart and facing southeast. Observations showed that the main visitors of cherry blossoms were *Andrena*, *Bombus*, *Lasioglossum* and *Osmia*, with *Bombus* being the most attracted to cherry flowers, while *Andrena* and *Lasioglossum* were more abundant in the surrounding landscape.

Fig. 12: Wooden log nest (left); wooden tray nest (right)

Osmia bees primarily occupied the artificial nests. No significant difference was found between the wooden log and tray nests in genus richness. However, wooden tray nests, though more expensive ($26.66/year) and complex to build, have a longer lifespan (at least five years), require minimal maintenance and allow easy cleaning and removal of parasitised cocoons. Pollinator abundance was significantly higher in Orchard 1, which was surrounded by pine forests and uncultivated land, compared to Orchard 2, which was mainly surrounded by cultivated land.

Research conducted in the province of Alicante in southeastern Spain explored which environmental conditions might boost the reproductive success of *Osmia* bees in trap nests located near almond orchards [31]. It was found that both local (small-scale) climate and landscape features (e.g., diverse vegetation, urbanisation level) affect nest occupation rate, brood productivity and parasitism rate, so *Osmia* bees near an almond field in the southern Mediterranean area would benefit from trap nest installation in well-sunlit, hot and humid sites with diverse vegetation.

ENCOURAGE THE PRESENCE OF AUXILIARIES TO CONTROL PESTS

Integrated pest management (IPM) relies on environmentally friendly strategies to regulate pest populations while minimizing the use of chemical pesticides. One of the most effective approaches is to encourage the presence of natural enemies, or auxiliaries, which help maintain ecological balance in agricultural systems. This can be achieved through cultural practices that create favourable habitats for beneficial organisms, as well as through biological control methods that leverage natural predators, parasitoids, and entomopathogenic microorganisms. This section explores how these two complementary strategies — habitat management and biological control — can be effectively implemented to enhance pest suppression in citrus orchards and other perennial cropping systems.

Cultural practices for pest control: example of the role of cover crops

In citrus orchards located in the Valencia region of eastern Spain, ground covers were composed of ~66% grasses (Poaceae), with the rest of the cover comprising mainly Malva sp. (13%), Oxalis sp. (5%) and Sonchus sp. (2%). Poaceae plants and *Oxalis* sp. harboured stenophagous aphids and Macrosiphum euphorbiae Thomas (Hemiptera: Aphididae), respectively, which appeared sooner in the system than citrus aphids. These aphids may serve as alternative prey or hosts for natural enemies and thus could enhance the biocontrol of *Aphid spiraecola*, the main aphid pest on citrus. By contrast, *Malva* sp. and *Sonchus* sp. harboured the potential citrus pest Aphis gossypii Glover and other aphids that appear simultaneously with *A. spiraecola*. By attracting these aphids to the cover vegetation, *Malva* sp. and *Sonchus* sp. may divert natural enemies away from *A. spiraecola* in the canopy, and therefore *A. spiraecola* might experience less predation or parasitism in the canopy. Although these wild plants may act as reservoirs for *A. spiraecola* as well as other aphid species that can disrupt the biocontrol services of natural enemies, overall, the sown cover was effective in terms of biological control of *A. spiraecola* in the citrus canopy. It promoted the early presence of predators in citrus canopies but did not promote the early presence of parasitoids. Predators attacked *A. spiraecola* colonies before their exponential increase. These attacks resulted in satisfactory aphid control, as citrus orchards with ground cover never exceeded the aphid economic threshold [32, 33].

Biological control: using nature to control pests

Natural control methods can be used to protect crops from pests as part of an integrated pest management approach, helping to reduce reliance on harmful pesticides and promote sustainable agricultural practices.

These methods involve the use of beneficial organisms/auxiliaries — all living organisms, predators and parasitoids — which can limit the spread of various crop pests. There are several types of biological control:

- Biological control by conservation, where the environment is managed to optimise the regulation of pests by naturally occurring beneficial organisms.
- Biological control by augmentation, where auxiliaries that are initially too few in number are added to the crop periodically.
- Biological control by inoculation or acclimatisation, when the agent introduced is exotic, originally absent, and the aim is to establish it permanently to limit the populations of an invasive pest.

Examples of biological control in citrus

Parasitoids to control orange spiny whitefly (OSW) (Aleurocanthus spiniferus)

Eretmocerus sp. gr. serius could represent a promising solution for the biological control of orange spiny whitefly (OSW) in Italy, where its presence has spread in recent years, while it has also been spreading elsewhere in Europe, with a particular northward trend. OSW is a new serious threat to citrus plants in the whole Mediterranean area, affecting host plants by sucking their sap. It also causes indirect damage by producing honeydew and subsequently promoting the growth of mould, leading to reduced yield and fruit downgrading. The importance of *E. sp. gr. serius* lies primarily in the fact that it is found in Italian territories invaded by OSW (Fig. 13). Therefore, unlike other allochthonous parasitoids, it should not require numerous, in-depth surveys for its introduction [34]. Under the current regulations, introducing a natural enemy is lengthy and laborious, slowing down the chances of prompt control and thus allowing the pest populations to spread further, cause damage and shift to other new host plants.

Fig. 13: A parasitoid wasp (Encarsia spp.) emerged from a dead whitefly prey. Photo: Arbico Organics

Parasitoids to control Aphis gossypii

The aphid *Aphis gossypii* is an efficient and common vector of the citrus tristeza virus (CTV), which results in costly pandemics that have reshaped the citrus world. Aphid control is mandatory to protect European citrus from CTV and can be done through i) beneficial insects, including the parasitoid *Aphidius colemani* and larvae/adults of the predatory coccinellid *Coccinella septempunctata* (Fig. 14, A & B) and ii) biopesticides active against aphids that are fungal pathogens (Fig. 14 C), such as *Verticillium lecanii* (Zimmerman), *Bauveria bessiana* (Bals.-Criv.) and *Paecilomyces fumosoroseus* (Wize). These biopesticides are harmless to beneficial insects and can be used jointly to enhance control efficiency. Beneficial insects and fungal pathogens should be released several times within the growing season, especially in spring and early summer, if infestation rates are high.

Predator Cryptolaemus montrouzieri to control Mealybug (Delottococcus aberiae)

The South African mealybug affects fruits and leads to substantial crop losses. There are no effective natural enemies in the native fauna. One of the main solutions is the release of the predator *Cryptolaemus montrouzieri*. This predator can be bred by farmers with the help and advice of local advisory services [35.] *Cryptolaemus montrouzieri* should be released on the citrus canopy of the predator from March onwards and at the larval stage (dose of 3/10 per tree, representing 1200–4000 adults/ha) to reduce pest levels at the time of maximum fruit sensitivity. To reduce the pest in the following year, releasing adults in summer at a dose of 3/10 per tree reduces the wintering population.

Examples of biological control in stone fruit orchards

Predatory mite Typhlodromus pyri to control sucking pests

Sucking pests, such as red spider mites, pear leaf blister mites and plum rust mites, often affect fruit trees and cause extensive damage to the fruits. The predatory *mite Typhlodromus pyri* can be a successful biological control solution for these sucking pests. The predatory mite *Typhlodromus pyri* (Fig. 15A) should be introduced to all fruit trees (pith and stone) using felt strips, where this predatory mite overwinters (Fig. 15B). One strip with ten individual predatory mites should be applied per tree, and the mites will begin to multiply and feed on pest eggs and larvae. Better results are expected in the second year after release, when the predatory mite has multiplied sufficiently. *Typhlodromus pyri* are introduced only once in the orchard; they remain on the trees for decades and suppress pests for the lifetime of the trees.

Fig. 14 Biocontrol agents effective against aphids; (A) the parasitoid A. colemani, (B) an adult ladybug; (C) entomopathogenic fungus Pandora neoaphidis. Photos: insectosutiles.es, mygarden.com and Shutterstock, respectively

Fig. 15 (A) The predatory mite Typhlodromus pyri; (B) felt strips with overwintered T. pyri; (C) tree branches in early spring. Photos: Martina Novotná (Biocont Laboratory) and Radek Vávra (VSUO), respectively

Examples of biological control in grapes

Predators of phytophagous mites

Vine mites can be both pests and helpers, depending on the species. Phytoseiids are predators of spider mites (phytophagous mites). The species *Thyphlodromus pyri* has shown good results in biological control through the introduction of populations into vineyards, although it has not been totally effective or repeatable. In vineyards managed rationally, it has been observed that phytoseiid populations frequently recover. For example, in a database of 58 plots managed using integrated pest management, the percentage of plots correctly supplied with *T. pyri* rose from 30% to 90% in the space of six years[36]. *T. pyri* is the major species in northern vineyards.

Biological control of Empoasca vitis

Several species of parasitoids can parasitise *Empoasca vitis* eggs. *Anagrus atomus* is by far the predominant species, responsible for 72% to 100% of parasitism on this leafhopper, with the other species playing only an anecdotal role. However, the rate of parasitism is not regular from one year to the next, no doubt in response to changing climatic conditions. In addition, a percentage of parasitised eggs of around 40% may not be enough to keep larval populations below the treatment threshold and sufficient to regulate *Empoasca vitis* populations[36].

Effect of bat Pipistrellus spp. in the biological control of Lobesia botrana

The European grapevine moth (*Lobesia botrana*) is the major pest in viticulture worldwide. This pest is effectively controlled with pheromones, however, this method only works when the vineyard is over 5 ha and is an expensive treatment (€100–300/ha depending on dose). Bats are the most suitable predators to increase biological pest control of European grapevine moths: one bat (*Pipistrellus* spp.) can eat between 1000 and 3000 insects per night. Installing bat boxes is particularly interesting in Mediterranean viticulture, and in the region of Valencia (Spain), the Cavanilles Institute of Biodiversity and Evolutionary Biology (ICBIBE) conducted the project 'Bat conservation in vineyards to control the European Grapevine Moth'. The main achievement of the project has been the steady growth of the bat population since the installation of the bat boxes, with an 80% occupation rate. Bat activity was notably higher in vineyards with bat boxes, exceeding 300 passes per recorder per night, and their hunting range extends up to 500 metres around the boxes. Bats contribute to pest control by preying on agricultural pests such as the olive fruit fly (*Bactrocera oleae*), olive moth (*Prays oleae*) and codling moth (*Cydia pomonella*) in addition to the European grapevine moth (*Lobesia botrana*). Importantly, no parasitoids or pollinators were found in their diet, highlighting their role as targeted pest regulators.

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CONCLUSION

The Mediterranean region faces unprecedented challenges from climate change, but the strategies outlined in this document offer a pathway to resilience and sustainability. By prioritising soil health through organic amendments, cover crops, and reduced tillage, farmers can enhance carbon sequestration and combat erosion. Water-efficient practices like deficit irrigation and smart technologies ensure optimal resource use, critical in an era of increasing scarcity. Biodiversity conservation, including the use of resistant varieties and agroecological practices, strengthens ecosystems and reduces dependency on chemical inputs. Innovations in post-harvest handling and food processing, such as innovative packaging and dealcoholisation techniques, address climate-induced shifts in crop quality and market demands. Diversification of income streams through agrotourism and value-added products provides economic stability while promoting circular economy principles. Collaborative efforts, supported by policies and research, are essential to scale these practices and foster widespread adoption.

The success of these strategies hinges on knowledge sharing, capacity building, and investment in sustainable infrastructure. Projects like CLIMED-FRUIT demonstrate the potential of integrated approaches to mitigate climate impacts and enhance agricultural resilience. As the Mediterranean navigates the complexities of climate change, adopting these practices will be crucial to preserving its agricultural legacy, ensuring food security, and maintaining ecological balance. By embracing innovation and sustainability, the region can build a resilient future for its farming communities and ecosystems.

CLIMED-FRUIT

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